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WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 138

DROUGHT AND AGRICULTURE

Report of the CAgM Working Group on the Assessment of Drought
prepared by C. E. Hounam (chairman), J. J. Burgos, M. S. Kalik,
W. C. Palmer and J. Rodda

WMO - No. 392

Secretariat of the World Meteorological Organization - Geneva - Switzerland

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THE WMO

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It was created:

— To facilitate international co-operation in the establishment of networks of stations for making meteorological and geophysical observations and centres to provide meteorological services and observations;

— To promote the establishment and maintenance of systems for the rapid exchange of meteorological information;

— To promote standardization of meteorological observations and ensure the uniform publication of observations and statistics;

— To further the application of meteorology to aviation, shipping, water problems, agriculture, and other human activities;

— To encourage research and training in meteorology.

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FOREWORD

The recent prolonged droughts in the countries on the southern fringe of the Sahara, in Ethiopia and in other parts of the world have demonstrated all too clearly the serious effects that rainfall deficiencies may have on agricultural production and hence on human well-being. The present Technical Note gives a systematic analysis of the drought problem from the agricultural point of view and should therefore be of interest to the agricultural meteorologist and to the agriculturist in the broadest sense of the word.

The report was prepared by the Working Group on the Assessment of Drought which was established some years ago by the WMO Commission for Agricultural Meteorology.

It gives me great pleasure to place on record the gratitude of the World Meteorological Organization to the chairman of the working group, Mr. C. E. Hounam, and to the other members of the working group, Messrs. J. J. Burgos, M. S. Kulik, W. C. Palmer and J. Rodda, for the time and effort they have devoted to the preparation of this publication.

D. A. Davies.

(D. A. Davies)
Secretary-General

SUMMARY

Drought, the precursor of famine, is undoubtedly one of man's worst natural enemies. Not only does it affect the social and economic life of millions of people every year, but from time to time the existence of whole nations is endangered. This report considers the many meteorological facets of drought including its definition and early recognition, its effect on plants, animals, and diseases, as well as its amelioration and methods for surviving under its influence.

An extensive survey is made of definitions of drought, classified according to whether they are based on rainfall only, on combinations of rainfall with temperature, humidity, wind or evaporation, on soil moisture *per se* or, more directly, on plant condition. Many of the early definitions are well-known indices of aridity or climate, such as those by Lang, de Martonne, Köppen and Thornthwaite, which are useful for drought studies when relatively coarse measures will do.

Special attention is given to various interpretations of the water-balance equation, one of the better-known examples being the Palmer model, which is explained in some detail. Other models such as that of Thornthwaite are included for their historical value. The use of the decile concept is also explained.

A chapter is devoted to agricultural practices under drought conditions covering the drought resistance of plants and seeds, the use of fallow as a management technique under dry conditions and the danger of erosion of drought-affected soils. The effects of drought on pastures and livestock are also considered: the behaviour of pasture species under drought is discussed, and it is concluded that pastoral management should be based on local or regional knowledge of drought characteristics with adequate adjustments between drought and non-drought periods.

The water requirements under drought conditions are also discussed, and it is shown that hydrological practices and structures can be used to lessen the impact of drought. The principal uses of water in agriculture are drinking (livestock), cooling (milk, buildings (air conditioning)), washing (livestock, vegetables, premises), crop spraying, frost protection and irrigation. In recent years studies by hydrologists of the streamflow-drought relationship have widened the scope of water resources management.

Another aspect of drought is its effect on the lives of various insects and pests and on disease, brought about by the reduction in moisture content of their natural environment. Although drought is in general adverse to agriculture, it has a measure of compensation in greatly reducing economic losses from some pests and diseases. Exceptions are the powdery mildews which often flourish in dry weather and aphids which migrate earlier from drying grass to alternate hosts such as crops and orchard trees and thus cause greater damage.

Certain agricultural practices can influence meteorological conditions in the plant/soil environment, and these may be used to advantage under drought conditions. For example, wind barriers can significantly reduce evaporation in their lee, thus reducing the demand on the store of soil moisture. Also a strategically timed fallow will eliminate the weed cover and thus conserve soil moisture for crop use later. The more controversial aspects of weather modification, such as the influence of forests on precipitation, evaporation suppression and cloud seeding, are also discussed briefly.

A section of the report is also devoted to methods of analysis. Application of standard statistical techniques which have already been used with some success in drought studies is discussed, and some examples are given. A brief review is also included of some examples of application of the water-balance equation, special attention being directed towards the evapotranspiration term and its reduction under conditions of drying soil.

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RÉSUMÉ

La sécheresse, avant-garde de la famine, est certainement l'un des pires ennemis naturels de l'homme. Non seulement elle perturbe chaque année la vie socio-économique de millions d'êtres humains, mais, de temps en temps, elle met en danger l'existence même de nations entières. Le présent rapport examine les nombreux aspects météorologiques de la sécheresse. Il donne notamment une définition de la sécheresse et énumère les indices qui permettent d'en faire un diagnostic précoce. Il passe en revue les effets de la sécheresse sur les plantes, les animaux et les maladies, ainsi que les moyens pour les pallier et les méthodes à appliquer pour survivre sous son emprise.

Le rapport contient un relevé complet des définitions de la sécheresse classées en fonction du ou des paramètres sur lesquels elles sont fondées, à savoir exclusivement sur les précipitations, sur une combinaison des précipitations avec la température, l'humidité, le vent ou l'évaporation, sur l'humidité propre du sol ou, plus directement, sur l'état des plantes. Un grand nombre des définitions connues antérieurement reposent sur des indices d'aridité ou des indices climatiques tels que ceux qui ont été élaborés par Lang, de Martonne, Köppen et Thornthwaite, indices qui sont utiles pour étudier la sécheresse, lorsque l'on peut se contenter de mesures relativement grossières.

Une attention toute particulière a été accordée aux diverses interprétations de l'équation du bilan hydrique, l'un des exemples le mieux connu étant le modèle de Palmer, qui fait l'objet d'explications détaillées. D'autres modèles, tels que celui de Thornthwaite, sont mentionnés en raison de leur intérêt historique. L'utilisation de la notion des déciles est également expliquée.

Un chapitre est consacré aux pratiques agricoles en période de sécheresse et traite de la résistance des plantes et des semences à la sécheresse, du recours à la jachère comme méthode d'exploitation en conditions de sécheresse et du danger d'érosion que courent les sols soumis à la sécheresse. Ce chapitre examine également l'influence de la sécheresse sur les pâturages et le bétail: il analyse le comportement des espèces fourragères en régime de sécheresse et conclut que l'exploitation des pâturages devrait être fondée sur la connaissance des caractéristiques de la sécheresse à l'échelon local ou régional, en tenant compte comme il convient des variations entre les périodes où la sécheresse sévit et celles où elle ne sévit pas.

Les besoins en eau, en régime de sécheresse, sont également analysés et il est montré que l'on peut avoir recours aux pratiques et structures hydrologiques pour atténuer les conséquences de la sécheresse. En agriculture, l'eau est principalement utilisée pour l'abreuvage du bétail, pour servir d'agent refroidisseur (lait, bâtiments (air conditionné)), pour le lavage (bétail, légumes, locaux), l'arrosage des cultures, la protection contre le gel et l'irrigation. Les études menées ces dernières années par les hydrologistes sur la relation existant entre le débit des cours d'eau et la sécheresse ont élargi le champ d'action ouvert à l'exploitation des ressources en eau.

Un autre aspect de la sécheresse est l'influence qu'elle exerçe sur la vie de divers insectes et parasites et sur les maladies des plantes, du fait de la diminution de l'humidité du milieu naturel.

Bien que la sécheresse soit généralement néfaste à l'agriculture, elle compense en partie ses inconvénients en entraînant une forte diminution des pertes que certains parasites et certaines maladies infligent à l'économie, encore qu'il existe certaines exceptions, telles que le mildiou poudreux qui se développe fréquemment par temps sec et les pucerons qui quittent plus tôt les herbes en train de se dessécher pour émigrer sur d'autres hôtes, plantes cultivées et arbres fruitiers, par exemple, où ils causent de plus grands dégâts.

Certaines pratiques agricoles peuvent influencer les conditions météorologiques du milieu que constituent la plante et le sol et l'on peut donc les utiliser avec profit en période de sécheresse. Par exemple, des brise-vent peuvent réduire de manière importante l'évaporation sous leur vent et limiter ainsi le prélèvement d'eau dans le sol. De même, une mise en jachère effectuée opportunément éliminera les mauvaises herbes en conservant au sol son humidité pour les cultures qui seront entreprises ultérieurement. Le rapport analyse aussi brièvement les aspects les plus controversés de la modification artificielle du temps et notamment l'influence qu'exercent les forêts sur les précipitations, le problème de la suppression de l'évaporation et celui de l'ensemencement des nuages.

Une section du rapport est consacrée aux méthodes d'analyse. On y expose, en s'appuyant sur un certain nombre d'exemples, comment appliquer les méthodes classiques de la statistique qui ont déjà été utilisées avec un certain succès lors d'études sur la sécheresse. Cette section fait également état d'un certain nombre d'exemples d'applications de l'équation du bilan hydrique, une attention toute particulière étant accordée à l'évapotranspiration et à la réduction de celle-ci lorsque le sol est en voie de dessèchement.

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РЕЗЮМЕ

Засуха, предшественник голода, является, несомненно, одним из наихудших естественных врагов человека. Каждый год она не только влияет на социальную и экономическую жизнь миллионов людей, но время от времени опасности подвергается существование целых народов. В настоящем отчете рассматриваются многие метеорологические аспекты засухи, включая ее определение и раннее распознавание, ее влияние на растения, животных и заболевания, а также мелиорация и способы выживания при засухе.

Дается обширный обзор определений засухи, классифицированных в соответствии с тем, основаны ли они только на осадках, на сочетании осадков с температурой, влажностью, ветром или испарением, по существу на влажности почвы, или непосредственно — на условиях растений. Многие из ранних определений Ланга, де Мартонна, Кёппена и Торнтвайта являются хорошо известными индексами засушливости или климата, которые полезны при исследовании засухи, когда подойдут относительно грубые измерения.

Особое внимание обращено на различную интерпретацию уравнения водного баланса ; одним из наиболее известных примеров является модель Пальмера, объясненная довольно подробно. Другие модели, такие как модель Торнтвайта, включены из-за исторической ценности. Объяснено также использование концепции дециль.

Одна глава посвящена практике ведения сельского хозяйства в условиях засухи, охватывая вопрос засухоустойчивости культур и семян, использования пахоты в качестве способа обработки при засушливых условиях и опасности эрозии почв, поврежденных засухой. Рассмотрено также влияние засухи на пастбища и животноводство ; обсуждается состояние видов пастбищ в условиях засухи и сделан вывод, что организация пастбищного хозяйства должна основываться на знании локальных или региональных характеристик засухи с соответствующим приспособлением между периодами засух и без засух.

Обсуждаются также потребности в воде при засухе и показано, что гидрологические методы и сооружения могут использоваться для уменьшения влияния засух. В сельском хозяйстве вода в основном используется для питья (животноводство), охлаждения (молока, помещений (кондиционирование воздуха)), мытья (животных, овощей, помещений), опрыскивания культур, предохранения от заморозков и ирригации. Проведенные в последние годы гидрологами исследования зависимости речной поток-засуха расширили сферу регулирования водных ресурсов.

Другим аспектом засухи является ее влияние на жизнь различных насекомых и сельскохозяйственных вредителей и на заболевания вследствие снижения содержания влаги в окружающей их естественной среде. Хотя засуха вообще приносит вред сельскому хозяйству, она в некоторой мере является средством компенсации в том смысле, что значительно снижает экономические потери, причиняемые некоторыми сельскохозяйственными вредителями и болезнями. Исключением является мучнистая роса, которая часто процветает в сухую погоду, и тля, которая раньше мигрирует с засыхающей травы на своих временных хозяев, таких как зерновые и садовые деревья, и наносит, таким образом, огромный ущерб.

Некоторые сельскохозяйственные мероприятия могут влиять на метеорологические условия в соотношении растение/окружающая почва, и они могут успешно использоваться при условиях засух. Например, ветровые заграждения могут значительно снизить испарение с подветренной стороны, сокращая таким образом потребность во влаге из почвы. Стратегически своевременная пахота также устранит покров сорняков и таким образом сохранит влагу в почве для ее более позднего использования культурами. Вкратце обсуждаются также наиболее противоречивые аспекты изменения погоды, такие как влияние лесов на осадки, уменьшение испарения и засев облаков.

Один раздел отчета посвящен также методам анализа. Обсуждены и даны некоторые примеры применения стандартных статистических методов, которые уже использовались с некоторым успехом при изучении засух. Включен также краткий обзор некоторых примеров применения уравнения водного баланса, особое внимание направлено на термин эвапотранспирации и ее уменьшение при условиях высыхающей почвы.

RESUMEN

La sequía, precursora del hambre, es sin duda alguna uno de los peores enemigos naturales del hombre. No solamente afecta cada año a la vida económica y social de millones de personas, sino que de vez en cuando pone en peligro la misma existencia de naciones enteras. En el presente informe se examinan los múltiples aspectos meteorológicos de la sequía, incluida su definición y su pronta identificación, sus efectos en las plantas, los animales y las enfermedades, así como la forma de mitigar tal desastre y los métodos que permiten sobrevivir bajo sus efectos.

En el informe figura un amplio estudio de las definiciones de la sequía, clasificada en función de las precipitaciones solamente, o en función de combinaciones de las precipitaciones y de la temperatura, de la humedad, del viento o de la evaporación, o únicamente en función de la misma humedad, o bien, más directamente, en función de las condiciones de las plantas. Muchas de las primeras definiciones constituyen índices conocidos de aridez o de clima tales como los de Lang, de Martonne, Köppen y Thornthwaite, muy útiles para los estudios sobre la sequía cuando pueden aplicarse medidas relativamente sencillas.

Se presta una atención muy particular a las diversas interpretaciones de la ecuación del balance hídrico, siendo uno de los mejores ejemplos conocidos el del modelo de Palmer que se describe con algún detalle. Otros modelos, tales como el de Thornthwaite, figuran simplemente a título histórico. También se describe la utilización del concepto de la decila.

Se consagra un capítulo a los métodos agrícolas utilizados en condiciones de sequía y relativos a la resistencia de las plantas y de las simientes a la sequía, a la utilización de barbechos como técnica de ordenación en condiciones secas y al peligro de erosión en los suelos afectados por la sequía. Los efectos de esta última en los pastos y en el ganado también son objeto de estudio; asimismo se examina el comportamiento de las especies de pasto en condiciones de sequía, y se llega a la conclusión de que la planificación de las tierras de pasto debe basarse en un conocimiento local o regional de las características de la sequía, con los reajustes indispensables entre los períodos de sequía y los períodos normales.

También se examinan las necesidades hídricas en condiciones de sequía y se demuestra que las prácticas y estructuras hidrológicas pueden utilizarse para reducir el impacto de aquélla. El agua se utiliza principalmente en agricultura para dar de beber (ganado), para enfriar (leche, edificios – climatización), para limpiar (ganado, vegetales, locales), para rociar las cosechas, para la protección contra las heladas y para el riego. En años recientes, los estudios efectuados por hidrólogos sobre la relación corriente-flujo-sequía han ampliado el concepto de la ordenación de los recursos hídricos.

Otro aspecto de la sequía lo constituyen sus efectos en la vida de insectos diversos, así como en las plagas y enfermedades, debido a la reducción del contenido de humedad del medio ambiente natural. Aun cuando la sequía es por lo general funesta para la agricultura, en cierto modo tiene un efecto de compensación al reducir notablemente las pérdidas económicas originadas por algunas plagas y enfermedades. Las excepciones son el oidio de los cereales que florece a menudo en tiempo seco, y el afídido que emigra más pronto de los pastos secos a otros cultivos, tales como las cosechas y los frutales de las huertas, causando así mayores daños.

Ciertas prácticas agrícolas pueden tener una influencia en las condiciones meteorológicas del medio planta/suelo, y esas condiciones pueden utilizarse ventajosamente en condiciones de sequía. Por ejemplo, las barreras contra el viento pueden reducir de manera muy significativa la evaporación en la zona abrigada, disminuyendo así las

necesidades de almacenamiento de humedad del suelo. Asimismo, el hecho de dejar oportunamente en barbecho ciertas tierras elimina la cobertura de yerbajos, conservándose así la humedad del suelo para los ulteriores cultivos. Los aspectos más controvertidos de la modificación del tiempo, tales como la influencia de las zonas forestales en la precipitación, la supresión de la evaporación y la siembra de nubes también son objeto de un breve examen.

Una sección del informe se dedica asimismo a los métodos de análisis. La aplicación de técnicas estadísticas normalizadas, que ya han sido utilizadas con algún éxito en los estudios de la sequía, son objeto de estudio y se dan algunos ejemplos. También figura una breve reseña sobre algunos ejemplos relativos a la aplicación de la ecuación del balance hídrico, consagrándose una especial atención al factor evapotranspiración y a su reducción en condiciones de sequía.

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CHAPTER I

INTRODUCTION

1.1 General

Drought is undoubtedly one of man's worst natural enemies. Its beginning is subtle, its progress is insidious and its effects can be devastating. Drought may start any time, last indefinitely and attain many degrees of severity. It can also occur in any region of the world, with an impact ranging from slight personal inconvenience to endangered nationhood.

The purpose of this report is to consider the climatological nature of drought with specific reference to agriculture.

1.1.1 *Drought and economic losses*

Food and fibre production is the vital end point of agricultural activities and from even a superficial survey it can be shown that losses from an extended continental drought can amount to many hundreds of millions of dollars. Direct losses result from reduced crop yields, pasture deterioration and livestock deaths, and a complete list would include reduced returns of most agricultural products. Other direct financial losses result from transport of emergency food supplies for humans and animals, establishment of emergency water supplies either by additional bores for immediate use or surface water storages for future use, and wind erosion. Estimates of indirect losses are more difficult to evaluate but would include losses from crops not planted and production from animals not conceived; also included would be losses due to abandonment of land, changes in land use following drought, and administrative costs resulting from the agro-economic and meteorological planning for alternative land use. Although the primary losses are borne by the agricultural and pastoral industries, the cost of drought is ultimately spread over a whole nation when the government makes relief grants to primary industries, assists with transport of fodder and livestock on agistment, constructs emergency water reservoirs, and when general price rises follow the shortage or import of commodities.

It is unlikely that an accurate integrated figure of world losses due to drought will ever be possible because of the great difficulty in isolating the direct cause of many losses but it would certainly amount to an enormous sum. Some of the complexities in preparing estimates are outlined by Heathcote (1969). The drought problem always exists somewhere in the world so that the economy of some nation or nations is always being adversely influenced by this factor.

It seems that there is scope for a world survey on the economics of drought as a basis for future improved planning which could lead to some reduction in the intensity of land use in some areas and possibly an increase in others.

1.1.2 *Drought versus aridity*

A study of drought requires an objective definition, but to date no universally acceptable one has been developed. Because of this it is felt that some introductory agrometeorological discussion is necessary before undertaking an assessment of definitions.

It can be assumed, without too much anticipation of the later section on definitions, that the basic cause of drought is inadequate precipitation. The meaning of the word "inadequate" is not considered at this stage. The most frequently applied method for rapid assessment of drought is to examine the incidence of rainfall at a point, or better, over an area.

The distribution of average annual precipitation across the world does not by itself give an indication of drought incidence or intensity although obviously it has a marked control over normal land use. The incidence of drought depends very much on the definition used; for example, by a definition based on available water, the arid zones of the world would be almost permanently drought-stricken, but by reference to normal rainfall they could be classified as less subject to drought than some "heavy" rainfall areas. It is important therefore to note the difference between aridity and drought. Definitions of both are discussed in Chapter 2.

Aridity is usually defined in terms of low average rainfall or available water and, ignoring the possibility of climatic change, is a permanent climatic feature of a region (Wallén, 1967). Drought, on the other hand, is a temporary feature in the sense that, considered in the context of variability, it is experienced only when rainfall deviates appreciably below normal. Aridity is, by definition, restricted to regions of low rainfall, and usually of high temperature, whereas drought is possible in virtually any rainfall or temperature régime. Activities in the arid zone are geared to meet the "permanence" of aridity but a drought situation results in at least some interruption of normal activities in all zones.

1.2 Drought and the water balance

1.2.1 *Soil water*

The prime factor controlling the water balance of the plant-soil environment is the water supply available to the plant. Every increment of water falling on the surface is partitioned according to the water-balance equation in the following way:

$$P = Q + U + E + \Delta W$$

where P is the precipitation or irrigation water added;
Q is runoff;
U is deep drainage passing beyond the root zone;
E is actual evapotranspiration;
ΔW is change in soil-water storage.

In extended rainless periods and in the absence of irrigation P, Q and U are zero. Therefore

$$E = -\Delta W$$

The actual evapotranspiration depends on changes in soil water and is usually much less than potential evapotranspiration which may be very high under these conditions (Figure 1). Drought in the agricultural sense does not begin with the cessation of rain but rather when available stored water will support actual evapotranspiration at only a small fraction of the potential evapotranspiration rate. This phase of the plant-soil-water relationship is quite complex and has been the subject of considerable investigation in recent years.

Although the physics of soil water is a complex subject, it is nevertheless relevant to drought and it will be necessary to define some terms. Further aspects of soil water are discussed by Kutilek (1971) and by WMO (1968).

The field capacity of a soil is the amount of water that a fully wetted soil contains after drainage has continued for one to three days (depending on soil type). Field capacity appears to be a more or less fixed quantity for a given soil but from the strictly physical point of view it varies too widely to be regarded as a constant.

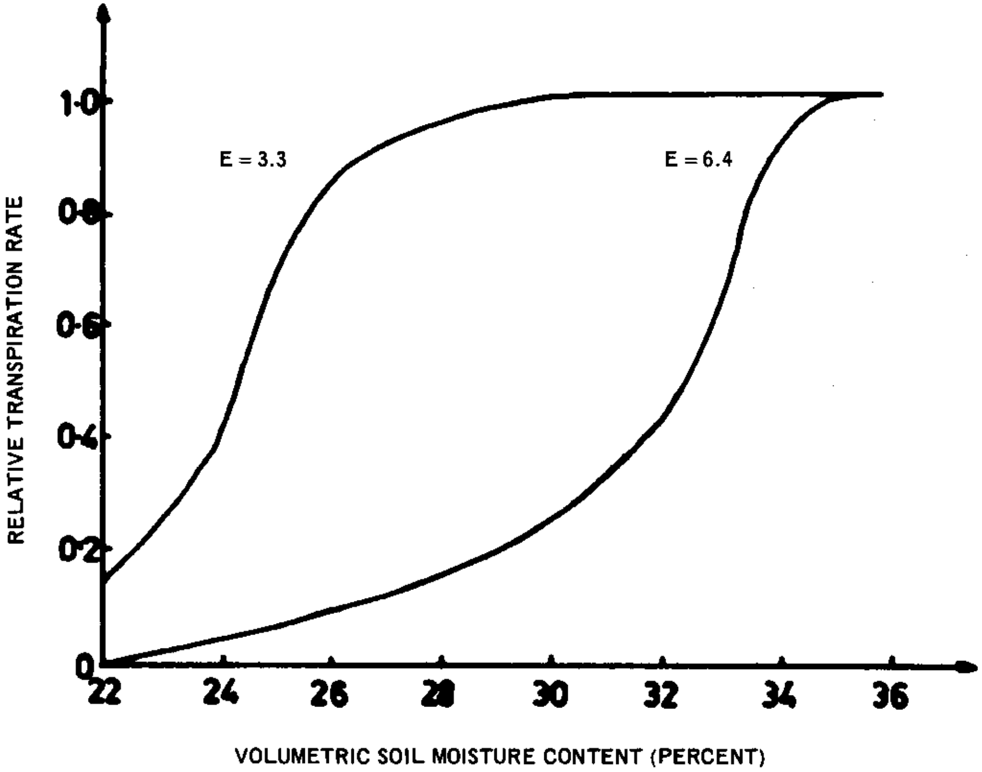

Figure 1 – Variation in relative transpiration rates with soil-moisture content under different potential transpiration conditions. (E = 3.3 and 6.4) (in mm/day). *(After Denmead and Shaw, 1962)*

The permanent wilting point of a soil is the upper limit of the amount of soil-water below which plants remain permanently wilted in an atmosphere of 100 per cent relative humidity. The soil-water potential at the permanent wilting point is usually accepted as –15 bars although this has been found to vary from –10 to –20 bars.

Available soil water is the amount of water retained in the root zone of a soil between field capacity and the permanent wilting point and is assumed to be available for plant growth.

The rate of transpiration by a crop depends largely on the availability of soil water as determined by the root system of the plants. As water within the main root zone becomes depleted, new root growth expands downwards and horizontally, tapping new sources of water. This helps maintain transpiration but usually at an ever decreasing rate. The presence of a water table within reach of the roots is advantageous for maintaining transpiration and growth during dry periods.

In a drought situation the dearth of soil water is often aggravated by an increased heat load imposed on the plant by net radiation because of less cloudiness and possibly lower albedo. Under such conditions the plant may be subjected to severe temperature stress with accompanying deleterious biochemical and physiological effects.

1.2.2 *Precipitation*

Over the greater part of the Earth's surface soil water is supplied by precipitation in the form of rainfall. However, in some areas of high latitude or high elevation the predominant form is snow. Fog and dew, almost without exception, are minor moisture sources. Hail is important because of the severe damage it often causes to plants; in times of drought, however, the areal benefit of the accompanying rain may more than offset the hail damage.

The role of snowfall in drought relief depends on several factors. The main contribution of snowfall might be to replenish the reserves of soil water accumulated prior to the beginning of the growing season. In areas of high precipitation, soil water is usually replenished by autumn and spring rains so that snow may be superfluous and contributes mainly to runoff and streamflow and, if the ground is not frozen, to deep percolation and the level of groundwater. In the more arid areas, snowfall is usually light and during drought periods may be negligible. Arid areas where snow may fall are subject to strong winds which prevent the accumulation of snow on open fields where it is needed. Advantage may be taken of the well-known barrier effect of windbreaks and shelterbelts to deposit a proportion of snow near the barrier at the expense of the area farther down wind (WMO, 1964). Depending on the amount of snowfall, the wind speed and the soil type, such barriers may or may not be of overall benefit to the relief of drought in a given area.

The areal variability of rainfall is well known, but superimposed on this is a marked small-scale areal variation brought about by the interception of rainfall by vegetation. Rain falling on individual plants tends to flow along stems to branches and trunk so that there is a greater concentration of water entering the soil near the base of the plant. This form of water collection depends to some extent on the shape of the plant; some which have branches and leaves which are inclined in a vertical position are more efficient collectors. Wind also has an effect on local rainfall distribution through its direct effect on interception by plants and the effect of the latter on wind speed and thus horizontal transport of drops. The rainfall which is required to wet the leaves of a plant is ultimately evaporated without passing through the plant and it is possible for none to reach the soil whence it would participate in the transpiration process.

1.2.3 *Dew and fog*

Another contribution to soil water may come in the form of dew but although some strong claims have been made regarding the amount of moisture available from this source, most studies over the last 10-15 years have indicated that dew cannot be regarded as making any significant contribution to drought relief except perhaps in the arid zone.

Dew formation is limited to a "no-rain" synoptic situation as it depends on surface cooling by radiation with a clear sky and a low wind speed (but not calm) to reduce heat exchange with higher levels. Other factors aiding dew formation are relatively high humidity and open shaped vegetation to maximize radiation losses. Dew may originate as condensation from the overlying air, as condensation of vapour moving upwards from the soil or as guttation, which is water exuded from leaves under conditions of high root pressure and near-zero transpiration. Thus, only dewfall from the ambient air can be regarded as an addition to the soil-plant water storage; the other forms may actually increase the soil water loss by bringing free water to the surface where it evaporates rapidly after sunrise.

Interception of fog by vegetation has been the subject of several investigations and although this process undoubtedly has a local effect on the water balance, it is insignificant in the context of drought.

1.2.4 *Surface runoff*

The effectiveness of rainfall depends considerably on the proportion which is lost by surface runoff. Under conditions of moderate- to high-intensity rainfall, runoff can reach values in excess of 90 per cent, whilst even in the case of low intensity, runoff can be high if soils are at or near saturation and rainfall is extended in time. Runoff can be divided into two types for the purpose of this discussion: first, that which enters a well-defined channel where it eventually contributes to groundwater recharge or reaches the sea; and, second, that which is redistributed within a small area by flowing from slight elevations to depressions. The latter type of runoff results in an accumulation of water at points in the field which may thereby receive an amount which is two or more times the depth of the rainfall.

There are also combinations of these two types of runoff. For example, a number of streams flowing inland from the mountain chain near the coasts of New South Wales and Queensland are fed by substantial rainfall which causes moderate to high streamflow with some flooding in the wet season. These streams flow towards the arid interior losing water progressively by evaporation and deep seepage. However, in some seasons there may be sufficient flow to cause flooding over a wide expanse of arid plain only slightly above stream-bed level. This is a special case of a natural irrigation storage in which drought in a favoured area of the arid zone is relieved almost every year by the addition of moisture precipitated up to a thousand miles distant. Ancient Egypt prospered by similar flooding of the Nile.

There is considerable evidence of redistributed runoff (or "run-on") and deep drainage in stream courses in many of the arid and semi-arid areas of the world. In Australia and the U.S.A. for example, it is common for trees to line dried water courses or, in many areas, to grow in the stream bed where they have access to stored water through a greater depth of soil and, in some instances, to the water table.

Shallow-rooting plants in the arid zone are mainly ephemerals which germinate, flourish and senesce in a relatively short period (a few weeks) following a limited fall of rain. Perennial grasses with much better-developed root systems are able to withstand moderately intense drought because of the wide area traversed by roots and large spaces between plants, thus reducing competition for water. Shrubs and small trees such as mulga *(Acacia aneura)* growing in areas not especially favoured by run-on from their surroundings generally withstand drought longer than pasture plants but complete or partial failures occur in severe drought. Groves of mulga in areas favoured by local redistributed runoff are generally able to withstand the most severe droughts. The most favoured vegetation in the drought-prone arid zones is that which grows in and along the water courses where soil moisture is replenished spasmodically, usually within a year, and water stored from deep drainage is available for extended periods to deep-rooted plants such as trees. Trees growing under these conditions are not likely to suffer excessively from drought unless some change in the hydrological characteristics of the area occurs, e.g. construction of a water storage upstream.

1.3 Fire hazard

Fire hazard in vegetation increases manifold during periods of drought. Forest fires are probably the most destructive of potentially commercial material. Grass and bush fires not only endanger the lives of livestock and man but also destroy a valuable source of feed for the farmer in times of drought. Standing or swathed grain which has been unduly dried by drought is very vulnerable to fire damage before or during harvesting operations. Not only do fires cause great economic loss in such cases but the destruction of wildlife is also great.

The assessment of drought from the fire hazard point of view and a fire hazard index are discussed in section 3.4.6.

1.4 Drought, ecological imbalance and soil erosion

In an environment in which man has exerted no influence, a climax or equilibrium state exists between climatic, topographic, soil and biotic conditions. The relative numbers of plants or animals of each species vary from season to season from year to year but changes tend to oscillate about a mean condition which is maintained unless there is a catastrophic event such as geological upheaval or major climatic change (Downes, 1968). Flood, fire or drought can also have a marked effect on the balance within an ecosystem but generally a reversion to normal would be effected within a relatively short period, say five years after a bush fire.

When man alters an ecosystem to improve its productivity, however, he may introduce new species of animals and new species of plants, remove vegetation by fire, machine or chemicals, cultivate soil, store water upstream, add water to soil by irrigation, and remove water from soil by drainage.

In pastoral areas man's intrusion usually means some overstocking and overgrazing with a subsequent reduction in plant cover even in good seasons, whilst under drought conditions native pastures usually suffer severely.

Farming operations, whilst probably increasing the overall productivity (at least temporarily), bring other changes which are not always beneficial, particularly in drought-prone areas. The main effects are to expose the hitherto protected soil to radiation, wind and rain. Local changes in the hydrological cycle are also sometimes induced.

Radiation falling on a vegetated surface is an essential ingredient to a good yield and, provided there is adequate water to maintain the transpiration stream, optimum conditions may be approached. However, once the soil, bared by drought, is exposed to direct radiation, there are marked changes in the heat balance. The soil becomes much hotter during the day and colder at night and these rapid changes result in other physical changes including disintegration of larger soil particles and hence greater erosion hazard. Extremely high surface temperatures may also cause a breakdown in humus with consequent biotic changes that reduce the soil quality as a medium for growing vegetation when drought ultimately breaks. Thus after extended drought new or intensified soil-erosion problems may arise.

With the intensification and continuation of drought, vegetation suffers and in the extreme case will die. For a short time the dead plant will continue to protect the soil but once it disintegrates the surface soil experiences a stronger wind flow by the nature of surface wind profile and reduction in surface roughness. The position becomes worse if the drought is long enough for dead roots to disintegrate and relax their binding influence on the soil.

Ironically, excessive rainfall during this stage of the drought can increase erosion if it is heavy enough to result in runoff. Some soils are relatively impermeable and bare when desiccated and small loosely bound particles will move readily under the action of water. Land management can therefore have a considerable influence on the protection of the soil from the ravages resulting from climatic extremes.

Some continents still have relatively large numbers of native herbivorous animals which rightly or wrongly are blamed for overgrazing, usually in competition with introduced animals. The position is often accentuated if a run of good seasons over several years results in a much better than normal supply of feed, leading to a temporary change in the equilibrium level and higher survival rate of young animals. This population increase eventually culminates in overgrazing and is arrested by the inevitable return to dry periods. The effect of drought can be made apparently worse by the tendency or need for animals to graze within a restricted area. Normally animals do not graze in an equal area pattern but are influenced by a number of controls, one of the most important in the arid and semi-arid zones being the location of water points. Animals graze within a more or less known radius of a water-hole and the centres of these areas are the first to become overgrazed and eroded in drought periods.

1.5 The space and time characteristics of drought

1.5.1 *Areal extent*

Drought can occur over areas of a few hundred square kilometres but almost invariably intensities are not severe and durations are relatively short. On the other hand, continental drought may extend over vast areas covering hundreds of thousands, or in extreme cases, millions of square kilometres. It is virtually impossible for a complete continent to be affected simultaneously although drought affecting about half of Australia might be expected once in fifty years.

Yevjevich (1967) quotes the results of a study by Caffey of inter-station correlation of annual rainfall in the United States. Arising out of this study, Yevjevich lists the following areal properties of continental drought:

(a) The average areal coverage of severe large continental droughts is of the order of 5 to 15 million square kilometres;

(b) The more severe a large drought, the larger is its areal coverage;

(c) The shape of the area covered by a drought is expected to be closer to an ellipse than to a circle.

1.5.2 *Beginning and end of drought*

Drought differs from other meteorological phenomena in temporal aspects. Its beginning and ending are often rather vague with respect to time, and its duration may be relatively long.

The term "beginning of drought" depends very much on the definition used. It obviously does not commence with the cessation of the last useful rainfall but may be related to this date through soil-water storage if this type of definition is accepted. The situation is often complicated by minor rains, sporadic in both temporal and areal pattern, which contribute negligible amounts to soil moisture but temporarily arrest the drying process. Even when an objective method is used, such as cumulated rainfall deficiencies or storage of soil water derived from a water balance, it is still necessary to establish reference points where the value of the objective index can be compared with direct observations of the condition of plants in the field. Even so, it is unlikely that a general conclusion would be arrived at, but rather, for example, that drought was under way with regard to, say, pasture and crops but not trees.

The problem is often just as great at the end of a drought except in those rather special circumstances where a rainstorm of pre-eminent proportions saturates soil to an appreciable depth over a wide area. Often relief arrives in an intermittent sort of way and moisture does not penetrate to the optimum depth to benefit the whole root system Thus, if not followed by more rain within a week or two, the drought situation could be just as serious again; in fact, it could be worse if fresh growth is initiated by useful rain and this tender growth is exposed to the harsh dry conditions of a resumed growing season drought. Palmer (1965) considered this problem in developing his drought analysis procedure and has devised criteria for objectively determining the end of drought periods. Briefly, he assumed that accumulated water shortages are gradually decreased when precipitation exceeds the "expected" amount and that small moisture excesses could be regarded as having terminated a brief mild drought; but large accumulated excesses are necessary before one can conclude that a long and serious drought has ended. Numerical criteria were derived from an empirical study of a number of cases of brief interruptions of drought and replacement of prolonged abnormally dry weather by prolonged abnormally wet weather.

1.5.3 *Duration*

It may be argued that if appropriate land use were cautiously followed in a particular climatic region, agricultural drought would be uncommon. For example, if agricultural or pastoral activities were conducted with reference to the median annual rather than the average rainfall, only about three years out of ten might be considered dry to very dry irrespective of whether the regions were in the humid or the arid zones. However, this tells very little about the duration or severity of drought, as a year of sub-normal rainfall could comprise a few months of extremely sub-normal rainfall followed by some months of above-normal rainfall. The same annual total could be accumulated from up to 12 months of slightly sub-normal monthly rainfalls.

Most places in the world are subject to drought in the agricultural sense but duration and intensity vary greatly from one climatic zone to the next. There are numerous occasions during the last hundred years when droughts over parts of the world's continents have continued unbroken for over 12 months whilst on rare occasions droughts have continued with negligible relief for nearly ten years.

1.5.4 *Persistence*

It may be shown statistically that runs of monthly rainfall above or below the median may, in some cases, exhibit a significant degree of persistence (Brooks and Carruthers, 1953). The effect is to decrease the number of short runs and increase the number of long runs as well as reducing the total number of runs (a further discussion of persistence appears in section 4.1.8).

There are also reasons for suspecting that drought may be self-perpetuating to some degree, that once the surface is bared of vegetation a greater quantity of sensible heat is returned to the atmosphere instead of latent heat. In these cases, there is greater surface heating and microturbulence and hence a far greater supply of soil-based cloud nuclei is mixed through a greater depth of the atmosphere. The preponderance of "continental"- over "maritime"-type cumulus cloud under such conditions could contribute to a persistence of drought (Twomey and Squires, 1959; Twomey, 1959).

1.5.5 *Climatic change*

A discussion of drought would not be complete without a reference to climatic change. During long drought periods it is sometimes contended that departures from normal are too extended to be part of the normal variability and it may be inferred that such drought is evidence of climatic change. The subject, which has been treated comprehensively by Unesco (1963) and others, is far too wide and complex to be covered here, but the following points should be noted.

In discussing plant ecology, Whyte (1963) refers to climatic change and lists the following types: major change into or out of ice ages or pluvials; minor changes which persist for 100 to 300 years; and variations or trends which are experienced for 10 to 50 years. (It is noteworthy that this classification does not include short-period variations in the general atmospheric cycles extending from a few months to a few years, i.e. significant drought periods.) Studies of the first two types may be carried out by the archaeologist, palynologist and palaeoclimatologist but, although significant historical dry periods have been identified they are, generally speaking, not very relevant in normal drought studies restricted to the periods of meteorological record.

Where minor changes (100-300 years) are recent, informative studies may be carried out by dendrochronology. As a climatic sensor a tree has the advantage that it occupies the same site throughout its life and may live for centuries, forming a distinctive growth ring each year. The size of the ring depends partly on available soil moisture but also in a complex way on light, temperature, leaf area and soil minerals. In drier regions (Fritts, 1963) trees can be selected for which sunlight, competition, exposure and soil factors remain essentially constant throughout their lives. Therefore growth-ring width becomes primarily a function of the limiting environmental factors, moisture and temperature. Soil moisture has been found to be the major limiting factor in the south-west United States.

Dendrochronologists are able to analyse the characteristics of growth rings and deduce index values which may be correlated with soil moisture, temperature, evapotranspiration etc. "Wet" and "dry" historical periods may be identified with fair accuracy. Fritts (1966) states that it is evident that a large portion of the variability in ring-width patterns from semi-arid sites in western North America does reflect differences in climate from year to year. If ring chronologies are derived from a number of trees in semi-arid sites and if adequate corrections for age and trend are made, these chronologies may be used to reconstruct a first approximation of annual, or somewhat longer-period, climatic fluctuations of the past.

1.6 **Causes of drought**

Drought might be most simply stated to be brought about by the lack of rainfall over an extended period of time, but this is not strictly correct as will be seen from an examination of some of the definitions in Appendix I, particularly those based on a water-balance model. A more accurate statement then is that agricultural drought is caused by an inadequate amount of soil-water available over a critical time period and this condition will depend also on plant species and soil type.

Drought is a regional manifestation of a general climatic fluctuation associated with persistent large-scale aberrations of the atmospheric circulation. Meteorologists can usually "explain" drought in a given region in terms of the abnormal atmospheric circulation patterns which favoured subsidence over the region. These explanations, however, of the immediate cause merely describe the concomitant meteorological motions and processes rather than the more fundamental dynamic and thermodynamic forces which produced the circulatory aberrations and their attendant meteorological by-products.

Although some have found it convenient to regard drought and similar climatic fluctuations as mere chance phenomena, it seems likely that these meteorological abnormalities are explainable in terms of *(a)* the physical forces and restraints which determine large-scale atmospheric circulation patterns, coupled with *(b)* regional and local factors which superimpose local climatic peculiarities on the large-scale climatic background. Of course, there are also those who believe that drought occurrences are rhythmic and therefore predictable by statistical methods. This, too, seems unlikely.

While ultimate causes of climatic fluctuations and variations have not been identified with certainty, a number of interesting hypotheses are under scrutiny. Generally speaking, these hypotheses can be separated into two categories, namely those which require variable extraterrestrial forces to account for circulation changes and those which treat the changes as self-evolving within the Earth-ocean-atmosphere complex. The ultimate explanation of drought includes any or all of the following, and possibly others.

The enormous heat-storage capacity of the oceans and the obvious energy exchanges which take place between the atmosphere and the oceans make air-sea interaction a likely cause of climatic variations. These interactions are extremely complicated and to date are poorly understood. However, it is difficult to see how this vast energy system can fail to contribute to climatic fluctuations.

It is also assumed that the injection of large amounts of ash and dust into the atmosphere by violent volcanic activity may alter the Earth's radiation balance and thereby create compensating circulation adjustments which induce climatic fluctuations. In the past, numerous volcanic eruptions have taken place with discernible effects, the most notable being the Krakatoa explosion in 1883, but the relative importance of this source of climatic change is by no means clear.

Also, there are substantial reasons for surmising that drought may result from changes in the composition of the atmosphere which could, in turn, produce alterations in certain characteristics of the large-scale circulation patterns. The gases most frequently mentioned in this connexion are water vapour, carbon dioxide and ozone, these being selective absorbers of radiation which could modify the heat balance of the Earth. Here again, evidence is meagre, but this must be regarded as another factor which, to some degree, could be responsible for climatic peculiarities.

Another hypothesis presumes that the amount and spectral quality of solar radiation varies continuously in an 80- or 90-year cycle (Lamb, 1972). There is such a cycle in the number of sunspots, but there is no positive evidence of such a cycle in the energy output of the sun. If such a cycle exists, the atmospheric circulation would be in a state of constant readjustment in accordance with the greater or lesser amount of solar energy reaching the Earth. As the readjustments evolve, drought would probably appear, first in one region then in another. There is an obvious and urgent need for an orbiting observatory that would continuously monitor solar output with greater precision.

1.7 Forecasting of drought

Examining the various methods which have been used to forecast long-term trends of weather, it seems that these could be classified as statistical, statistical-physical, analogue or physical-numerical.

Mitchell (1968) discusses the physical causes of climatic fluctuation and concludes that it may be possible to predict changes if the following conditions are met:

(a) A climatic variable is statistically autopredictable from a knowledge of its own past history;

(b) A climatic variable is statistically correlated with one or more environmental variables that in turn are statistically autopredictable;

(c) A climatic variable is prescribed through established physical cause-effect relationships by one or more governing environmental variables that in turn are statistically autopredictable;

(d) A climatic variable is prescribed through established physical cause-effect relationships by one or more governing environmental variables that in turn are physically autopredictable;

(e) A climatic variable is statistically correlated with one or more environmental variables that are physically autopredictable.

Mitchell further indicates that none of the above has been particularly successful up to the present and that *(a)* and *(b)* have been stressed almost to the exclusion of the other conditions for want of an adequate understanding either of the physical links between climate and the Earth's environment or of the physical laws that govern the temporal variability of that environment. A classic illustration is that of the 11-year sunspot cycle, the quasi-regular statistical behaviour which lends itself well to *(b)* above, whereas our physical insight into the cause of the cycle, together with our knowledge of the nature and magnitude of concomitant changes in solar energy output that are likely to affect tropospheric conditions, is hopelessly inadequate for pursuing *(c)* *(d)* and *(e)*.

A great many studies of the purely statistical type have been carried out but these have been generally unsuccessful in forecasting rainfall and, in particular, drought. For example, many apparent periodicities have been detected but none has been developed for use as a practical forecasting tool.

The statistical-physical method differs from the purely statistical method in that the relationship being investigated is between rainfall and some meteorological condition known to exert a control. For example, it has been found that in some regions there is a correlation between rainfall and pressure differences at two significant locations representing atmospheric circulation; however, such relationships are usually too tenuous to provide useful forecasts. Another method relates rainfall and sea-surface temperature conditions but in this case the method breaks down, partly because of lack of observations of surface temperature and ocean circulation.

The analogue method assumes that a similar meteorological situation in the past will develop currently in the same way. A formidable deterrent to testing the method has been the vast amount of labour involved in assembling and processing the data, particularly in selecting suitable analogues, but this task has been eased somewhat by the modern computer. A method based on analogues has been used in two or three countries to produce 30-day forecasts and results are claimed to be better than chance. Drought forecasts would therefore be based on features such as the departure of pressure systems from their normal latitudinal tracks and the non-formation of tropical cyclones. The method obviously becomes more difficult to apply with increasing length of period.

The numerical method integrates the basic equations of motion and thermodynamics of the atmosphere and by applying heat and vapour fluxes anticipated during the forecast period it is possible to compute the effects on the general circulation. Research in this area using computers is still in its infancy but may result in usable forecasts for as long as 30 days. Forecasts of the outbreak of drought have little significance over a period as short as this but are extremely valuable with respect to cessation of drought.

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START INDEX

CHAPTER 2

DEFINITION OF DROUGHT

2.1 Classification according to criteria

As indicated in the introduction, drought has many different facets. The approach by various investigators varies according to their particular interests and background and it is not surprising that a wide range of definitions has been developed. Many definitions have been designed to approach the study of drought in a particular way, often making approximations or substitutions where data such as evaporation are not available. Many are modified versions of earlier definitions and their inclusion here is mainly for historical reasons.

A general survey of definitions indicates that they can be classified according to the criteria used. Variables which are in use either alone or in combination are rainfall, temperature of air, humidity of air, evaporation from free water, transpiration from plants, soil moisture, wind, streamflow and plant condition.

Some definitions specify a temporal control whilst others are independent of time.

Most of the above variables have been discussed in the first section of this report and amplification of many of the salient features follows in later sections. Classification of drought definitions is given in Appendix I under the following sub-headings:

(a) Rainfall;
(b) Rainfall with mean temperature;
(c) Soil water and crop parameters;
(d) Climatic indices and estimates of evapotranspiration;
(e) General definitions and statements.

Obviously rainfall is the most important single factor influencing the incidence of drought and pratically all definitions use this variable either singly or in combination with other meteorological elements.

Many definitions of drought are based on the adaptability of husbandry to the "average" conditions and the importance of this is stressed in this report. For example, a pastoralist, raising fat lambs on improved pastures with a uniformly distributed rainfall averaging, say, 1000 mm a year, might be troubled by the relative "dryness" in a year producing only 750 mm, irrespective of its temporal distribution. To another pastoralist in semi-arid marginal agricultural country normally receiving 300 mm a year, this total of 750 mm would represent a record wet year, bringing with it the troubles associated with excessive moisture, namely waterlogged soils and pastures, lodged crops, untrafficable roads and ploughing or harvesting difficulties. The agriculturalist or pastoralist, especially in the drier regions, has assessed the nature of local rainfall and, through years of long and sometimes bitter experience, has learnt to adapt his operations to rainfall characteristics of the area. This is particularly the case in those areas with a long history of land use, in some instances extending back beyond historic times. Folklore, tradition and the passing on of personal experience through generations of operations on the same piece of land have all helped to determine a land use which has the greatest chance of success within the existing technological and scientific limitations. Where relevant advances in the latter fields have been made, it is possible to say in some instances that the risk of drought under the same climatic conditions has been eased but never erased. This of course does not include areas where irrigation has been introduced. Examples of progress in the struggle against drought are the development of drought-resistant strains of pastures and crops and more efficient equipment and machinery; thus greater advantage might be derived from a limited amount of feed available to a grazing herd aided by better transport for auxiliary feed and stock on agistment. However, although these factors may ease slightly a serious drought situation, they do not affect the objective definition of drought based on meteorological elements.

2.2 Definitions based on rainfall

Looking more closely into definitions based solely on rainfall it will be seen that a number of these refer to short-period "droughts" or better, "dry spells" (Appendix I). Typical examples of these are:

(a) Less than 2.5 mm in 48 hours;
(b) Rainfall half of normal or less for a week;
(c) Ten days with rainfall not exceeding 5.0 mm;
(d) 15 days with no rain;
(e) 15 consecutive days, none with 0.25 mm;
(f) 15 consecutive days, none with 1 mm;
(g) 21 days or more with rainfall less than 30 per cent of normal;
(h) 21 days with precipitation less than one-third of normal.

These appear to be tied mainly to climatic experience in the British Isles and Europe or perhaps the north-eastern U.S.A. where rainfall is normally received at fairly frequent intervals and crop and animal husbandry and water-storage operations are not geared to the long spells of rainless weather which are seasonally normal in some of the semi-arid regions.

TABLE I *(a)*

Rainfall percentile information in points at Katherine (Australia)
(100 points = 1 inch = 25.4 mm)

Station	*Item*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
Katherine P. O. Latitude 14° 6′ S Longitude 132° 40′ E 1073-1965 93 years Station No. 14030	Low	276	40	0	0	0	0	0	0	0	0	3	139	1730
	10	404	271	96	0	0	0	0	0	0	3	80	323	2431
	30	609	546	356	0	0	0	0	0	0	18	196	491	3120
	50	784	755	515	44	0	0	0	0	0	67	274	712	3793
	70	1074	971	805	143	3	0	0	0	8	153	370	946	4341
	90	1537	1289	1170	396	95	18	2	1	82	312	668	1321	5109
	High	2774	1928	2548	838	243	213	81	76	358	585	1400	2961	5891

Examine, in contrast, the normal rainfall experience at a tropical location such as Katherine in the Northern Territory of Australia (Table I *(a)*). It will be seen that the 50 per cent (or median) values of monthly rainfall are zero for each of the months May to September and even at the 90 per cent level rainfall is so low in these months as to make little contribution to plant growth. Furthermore, considering total rainfall for several months (Table I *(b)*) there is, for example, a 50 per cent chance that rainfall during the six months April to September will be 24 mm (0.94 inches) or less, whilst there is a 90 per cent chance that the total for the four months May to August will be 32 mm (1.27 inches) or less. It follows that it is almost certain that there will be a winter moisture shortage in this climatic environment. Thus, in this climatic zone drought definitions based on periods of a few days or weeks have practically no significance. By this definition drought incidence here is regular and predictable because of the seasonal rhythm but it does not represent a serious hazard to agriculturalists or pastoralists because local operations are geared to this experience. Through the process of long-term adaptation, nature has established native pastures which hibernate after the cessation of summer growth and autumn maturation. Pastoral activities are maintained on the existing body of dry feed and crops dependent on natural rainfall are not planted until the time when the spring rains normally occur. In fact it is possible for unseasonal rain in this climatic environment to cause serious damage to standing dry feed and thus bring on a pastoral drought, if we define this as shortage of feed for stock. Regrowth does not normally follow such unseasonal rainfall and, if it did, it would be unlikely to survive without the unlikely event of significant follow-up unseasonal rains. However, the period of concern in these climatic zones is the summer wet (growing) season when a break of a month or so without significant rain to maintain crop growth or even the delay of the onset of the spring rain often signifies the commencement of drought. These features are also brought out in Table I *(b)*.

TABLE I *(b)*

Details of rainfall experience in consecutive months commencing with the month indicated

Number of months	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
10th percentile value												
1	404	271	96	0	0	0	0	0	0	3	30	323
2	909	677	135	0	0	0	0	0	13	132	649	1027
3	1375	731	157	0	0	0	0	3	132	686	1251	1636
4	1489	828	159	0	0	0	9	132	686	1209	1893	2107
5	1489	834	159	0	0	10	143	686	1356	1938	2444	2155
6	1489	834	159	0	11	143	686	1356	1940	2487	2494	2166
7	1489	834	161	17	161	686	1356	1940	2488	2586	2494	2166
8	1489	835	256	206	687	1356	1940	2488	2610	2593	2497	2166
9	1489	925	531	741	1356	1940	2489	2610	2610	2598	2515	2166
10	1635	1157	964	1431	1962	2497	2610	2610	2610	2615	2515	2185
11	1917	1658	1803	2078	2499	2610	2610	2610	2627	2615	2522	2292
12	2431	2400	2435	2569	2654	2610	2610	2627	2627	2618	2660	2547
50th percentile value (median)												
1	784	755	515	44	0	0	0	0	0	67	274	712
2	1641	1304	669	69	0	0	0	0	96	389	1061	1602
3	2195	1426	685	71	1	0	0	96	425	1192	1935	2423
4	2394	1435	694	71	3	5	98	432	1216	2027	2581	2929
5	2452	1435	694	78	15	103	432	1216	2089	2022	3330	3118
6	2452	1435	697	94	120	433	1216	2089	2844	3424	3508	3118
7	2452	1455	698	233	433	1218	2101	2850	3424	3597	3506	3118
8	2452	1484	889	607	1233	2122	2850	3424	3597	3597	3506	3118
9	2452	1698	1203	1335	2126	2805	3424	3624	3597	3597	3506	3110
10	2556	2068	2080	2269	2886	3424	3624	3624	3597	3597	3506	3120
11	2875	2873	2951	2998	3424	3626	3624	3624	3597	3597	3506	3266
12	3793	3628	3754	3495	3650	3626	3624	3624	3597	3597	3562	3650
90th percentile value												
1	1537	1289	1170	396	95	18	2	1	82	312	668	1321
2	2409	2321	1331	400	112	32	15	101	367	800	1737	2509
3	3417	2321	1356	402	127	41	101	367	855	1907	2948	3431
4	3576	2335	1378	402	127	127	369	855	1946	3983	3736	4196
5	3586	2391	1378	402	215	376	655	1946	3148	3818	4600	4321
6	3586	2391	1378	463	464	855	1946	3148	3850	4733	4695	4321
7	3586	2391	1413	729	904	1958	3148	3850	4766	4877	4697	4321
8	3586	2391	1557	1164	1959	3182	3850	4773	4887	4877	4897	4324
9	3592	2457	2013	2153	3249	3858	4773	4887	4887	4877	4697	4324
10	3647	2900	3004	3421	4015	4779	4688	4887	4887	4885	4697	4371
11	3946	3849	4025	4399	4785	4888	4888	4887	4895	4855	4700	4326
12	5109	4971	4943	5049	4890	4888	4888	4895	4895	4885	4889	4962

A number of indices of aridity have been developed primarily for climatological studies and some of these may be applied to drought studies. Wallén (1967) discusses a number of such indices, and, in analysing some of their weaknesses, states that they may be misleading in the hands of inexperienced workers.

Definitions which do not specifically include duration have a wide application and have been used with success in the drier continents of the world. The use of percentiles quoted above is a good example of this type of definition but others, which appear to have been popular in the United States, refer objectively to some percentage level of normal rainfall. For example, Bates (1935) indicates that a state of drought exists when annual rainfall is 75 per cent of normal or when monthly rainfall is 60 per cent of normal.

2.3 Availability of soil water

Assuming that the ultimate indicator or definition of agricultural drought is some measure of the availability of soil water to plants it is interesting to look at attempts made to improve on the simple rainfall definition. Russell (1896) appreciated that the Australian drought situation differed appreciably from that of England whose climate was better known to most early Australian meteorologists. He was well aware of the significance of rainfall variability in drought study and added that other "important factors are great heat and drying wind".

The importance of evaporation was also recognized by Dokuchaev (late nineteenth century), Transeau (1905) and Vysotsky (1905) who used the *P/E* index to assess the effectiveness of rainfall. This ratio, with various significant levels representing different degrees of soil water, has been used by many workers throughout the world since its initial development.

The use of mean temperature by Kolostrov (1925), Selyaninov (1930), Knochenhauer (1937) and Thornthwaite (1931) were compromise attempts to incorporate a measurement of evaporation in the drought index because of the generally existing paucity of this type of observation. Considerable success has been claimed for these temperature-based models but caution must be exercised in applying them outside the region or climatic conditions where they were developed. However, there is no doubt that they have provided valuable information in the past and until more refined data become available they are likely to help fill the gap.

A number of attempts have been made to incorporate into moisture indices some measure of saturation deficit, supposedly as an indicator of the drying power of the atmosphere. Examples of these are the relationships of the Delton type used by many workers to estimate free water evaporation, the Popov (1948) relationship using wet-bulb depression, and the Ivanov (1948) relationship, which embodies humidity and temperature.

The term "atmospheric drought" is sometimes used to indicate an abnormal dryness of the air and many definitions using saturation deficit would be classified under this. In the literature of the U.S.S.R. the word *sukhovei* is used to describe a particular case of atmospheric drought in which the harmful effects of high vapour deficit are intensified by higher than usual temperature and an extended period of moderate to strong wind. The duration of the *sukhovei* may be less than a day or as long as several lays but the intensity of the drying effect on crops depends very much on available soil water. Feldman (1957) gives the five types of *sukhovei* weather (Table II).

The more sophisticated drought models use some measure or estimate of soil water and in most instances are specific examples of the water-balance equation. The Fitzpatrick (1965) method described in section 4.2.3 and two or three other related models used in Australia and in Canada (Sly and Baier, 1971) in recent years follow this procedure; they are an improvement on earlier water-balance models in that evaporation, more realistically, is made inversely proportional to the soil-water store.

The Palmer (1965, 1968) method, which is also amplified in section 4.2.4, is another water-balance method which relies on estimates of evapotranspiration derived from Thronthwaite's equation using mean temperature. An adjustment is made so that actual evapotranspiration falls below the potential rate under dry conditions.

TABLE II

Meteorological characteristics of the various types of *sukhovei* weather

Relative humidity (per cent)	*Mean daily temperature (° C)*	*Saturation deficit (mb)*	*Sukhovei category*
21-40	22.5 - 27.4	23	Weak
41-60	27.5 - 32.4		
0-20	22.5 - 27.4	29	Moderate
21-40	27.5 - 32.4		
41-60	32.5 - 37.4		
0-20	27.5 - 32.4	40	Intense
21-40	32.5 - 37.4		
0-20	32.5 - 37.4	51	Severe
0-20	37.5 - 42.4	67	Extremely severe

Workers in the U.S.S.R. have also long been aware of the importance of evaporation in assessing soil-water storage. The measure of drought intensity used by Kulik (1958) is the discrepancy between the water demands on the plant and the available soil water. Water demand depends on meteorological conditions, biological features of the plant, stages of development and availability of nutrients in the soil. Another factor considered by Kulik is the level of agronomic technique and it can be readily shown that all yield decreases are not due to drought. Drying out of the upper layer of the soil during the period of vegetative growth is an important index of drought intensity because root activity, nutrient supplies and the activities of useful micro-organisms are greatest in this layer. In the U.S.S.R. comparison of crop state with soil water has led to the conclusion that a decrease of available water in the arable layer (to 20 cm of soil depth) to 19 mm and to 9 mm indicates the beginning of a dry period and a very dry period respectively. Available water from sowing to flowering in the two soil profiles, 0-20 cm and 20-100 cm, is also used to predict yields of spring grain; if spring is preceded by a ten-day period during which soil water in the arable layer is less than 10 mm, then yields are reduced by almost 30 per cent.

2.4 References

(See Appendix I).

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CHAPTER 3

METEOROLOGICAL INDICES OF AGRICULTURAL DROUGHT

3.1 General

While some scientists have used meteorological data to develop methods for computing the extent and severity of agricultural drought, some of their colleagues have maintained that meteorologically derived drought indices were useless. The opponents of drought indices are, essentially, pointing out that the problem is so complex that no single index can possibly take full account of all the pertinent physical and biological factors. In view of this disagreement, a few comments are in order as to what drought indices are and are not, what purposes they serve and fail to serve, and something about the different kinds of drought indices.

Inasmuch as drought is regarded here as abnormal dryness, rather than a climatic state or type, the various indices of aridity, designed to delineate or characterize climatic types, are not considered to be true drought indices. Those interested in climatic indices will find that numerous authors such as Dzerdzeevskii (1958) and Wallén (1967) have summarized many of the empirical aridity indices which have been developed over the years by climatologists, geographers, ecologists and others. Such famous names as Oldekop, Lang, Köppen, de Martonne, Meyer, Thornthwaite, Ångström, and Emberger are prominent in most such accounts.

3.2 Agricultural drought

Specifically, the present discussion is limited to indices of agricultural drought which are defined as derived numbers or letters which indirectly express the degree to which growing plants have been adversely affected by an abnormal moisture deficiency. The deficiency may result either from an unusually small moisture supply or an unusually large moisture demand. While a deficiency in the water supply for livestock would ordinarily be regarded as a facet of agricultural drought, it is really a different problem because it does not depend primarily on soil moisture. Actually, one can best treat a shortage of livestock water as a part of the problems of hydrological drought, an overlapping but essentially separate subject which is briefly introduced in Chapter 6. The separateness is exemplified by the fact that a study concerned with agricultural drought would consider "effective rainfall" as being that portion of the rain that was retained in the root zone, while in hydrological drought "effective rainfall" is the portion which does *not* enter or remain in the root zone, but escapes by surface or subsurface drainage to augment the water supply in aquifers, streams, lakes, or ponds.

3.3 The purposes of an index

3.3.1 *To evaluate climatic proneness toward aridity*

One fairly common and simple use of an aridity index is that of determining the drought proneness or drought potential of an area, usually in very general terms. For example, Tumertekin and Conturk (1956) applied the de Martonne index of aridity, $P/(T+10)$, to annual values to derive the frequency of occurrence of various degrees of aridity during the period of record at 86 meteorological stations in Turkey. They found that the derived index values closely conformed to a Gaussian distribution at all stations, as one would expect. Therefore, the mean and the standard deviation of the index enable one to prepare such things as a map showing the mean interval between years of any specified degree of aridity. One might regard such studies as a sort of preliminary site evaluation in terms of drought potential. Unfortunately, simple empirical indices such as that of de Martonne do not necessarily produce a realistic assessment of the agricultural limitations imposed by drought.

3.3.2 *To estimate areal irrigation requirements*

To gain additional information on the seasonal cycle and frequency of water deficiencies, time periods shorter than one year should be studied using monthly, decadal or daily water-balance accounting over a long period of years. Evapotranspiration deficits can be computed by one of the meteorological procedures, using various assumed water-storage capacities of the root zone. The van Bavel (1953) (1959) studies are of this type. The results can be expressed either in terms of the total amount of time, e.g. number of days during the growing season, that crops would have suffered from a lack of soil water or in terms of the total depth of additional water that would have prevented the soil-water shortage. One may regard either of these two types of result as a sort of drought index. From these data frequency distributions can be prepared which show a type of climatology useful, for example, in determining the frequency of various levels of areal irrigation requirements, thus helping to answer some general questions such as those concerning the feasibility of a large irrigation project.

Studies of this sort are often criticized on the basis that they do not properly take account of all the factors which have a bearing on the water balance of specific crops at specific places and times. Such criticisms have some validity, but in general they stem from confusion as to the objectives of such a study. The refined type of study envisioned by the critics explains phenomena taking place locally. It does not ordinarily produce results in terms of an index, so it is rather outside the realm of this discussion. Nonetheless, a few remarks on the subject may help to dispel some of the confusion.

3.3.3 *To evaluate drought in a local setting*

The detractors of the index approach tend to concentrate their attention on the water status of a particular crop growing on a particular soil at a particular time and place. In general, only two types of individual have an interest in information of this sort, namely the professional experimenter who is trying to measure, understand and explain the basic physical and biological processes going on, or the farmer who is growing this particular crop. Those who maintain that this is the only type of index that can be used for regional or areal estimates of crop water conditions have never thought about the problem in realistic terms.

Some of the sorts of information that must be incorporated into a procedure which accurately and continuously reflects the water status of a specific crop at a specific site should be considered. Basically, there are three problems: the capability of the environment to induce evaporation and transpiration, which is really the energy aspect; the capability of the soil and plants to provide water for evaporation and transpiration; and the capability of the atmospheric environment to accept and disperse the vapour stream being fed into it from the soil and vegetation.

The first problem involves measurements of radiation and the horizontal advection of sensible heat. The second requires an assessment of the efficiency of the soil-plant system as a reservoir and "pump" for supplying water to evaporate and this introduces such problems as the physical and chemical composition of the soil, including its water retention and release characteristics throughout the root zone.

The amount of water added to the soil surface by rainfall and irrigation must be measured. This is essentially impossible over a field which covers a few acres; the best that can be done is to sample the rainfall by gauges which, even at best, sample only an infinitesimal fraction of the area. Then, the fraction of the rainfall which actually entered and was retained in the root zone must be measured or computed. This brings in infiltration rates, surface and subsurface drainage, and deep percolation. It usually requires precipitation measurements at short time intervals – hourly will often be inadequate.

The crop itself must be taken into account in terms such as osmotic pressures, stomatal behaviour and the extent to which its root system ramifies the soil. Also, the wetness of the soil surface and vegetation enters the picture. At times vapour transfer within the soil becomes very important, requiring consideration of the vertical temperature profile in the soil.

The third problem, the atmospheric acceptance and transport of the water vapour, involves measurements of the profiles of wind speed, temperature and humidity. For a particularly lucid account of the intricacies of the aerodynamics and energetics of the evaporation problem and a working approximation formula for routine use in irrigated areas and for climatological surveys, see Penman *et al.* (1967).

Obviously, these numerous requirements define a situation nearly identical to many research projects which have been carried out. However, thinking in terms of regional surveys or of providing some sort of drought warning or drought advisory service to all the agricultural interests over a large area, even as small as 100 km square, it is abundantly clear that the very sophisticated and scientifically precise type of information outlined above is simply out of the question. Such a system would cost too much to install and operate, and it would be too cumbersome to work very well anyhow. A regional survey or an areal assessment of the progress of a drought need not account for the condition or status of each plant nor even each field in an area in order to be reliable and informative. Actually, those having broad areal interests in this type of information would not want such detail, even if it could be furnished.

3.3.4 *For periodic reporting of the severity and regional extent of drought*

This brings up one of the most useful purposes for which a drought index might be constructed, namely as a device for summarizing and periodically disseminating drought information and crop moisture conditions on a regional basis. This type of information is needed by government agencies and other groups having wide regional or national interests or responsibilities, usually in terms of crop progress and/or production prospects. Many groups that need this type of integrated information find it rather difficult to obtain.

Thus, there are two primary uses for an index of agricultural drought, namely for evaluating the drought hazard over a sizeable area, often in comparison with other areas, or for periodic assessments of the current extent and severity of drought over a region. Neither of these requires the great detail associated with specific local conditions, but they do require procedures which realistically reflect the areal mean rates of water income and outgo in the area.

Actually, the procedure that fits one of these purposes may not be suitable for the other. An index being used for the routine assessment of the status of an existing drought is essentially a method for keeping track of the cumulative effects of a period of abnormally dry weather. The assessment must be made every few days if it is to reflect realistically all the important weather events which occur. Monthly assessment is too infrequent; too much happens to a crop in a month. Daily assessment is ideal, but it results in a great amount of repetitive detail. It appears that an assessment every five to ten days is a suitable compromise.

On the other hand, an index being used in a drought hazard survey does not require such a short time-period because the object is to evaluate the climate rather than the weather. Monthly data serve reasonably well for this purpose, but semi-monthly would be better. Too much information is lost if only annual values are used.

3.4 **Drought index examples in practice**

3.4.1 *Potential evapotranspiration* (PE) *methods*

The literature contains surprisingly few examples of meteorologically determined indices of the severity of agricultural drought. As mentioned above and in Chapter 2, there are numerous examples of aridity indices which are actually indices for climatic classification, but most of them are somewhat crude, empirical and of dubious value for agricultural purposes.

There are many meteorological procedures for computing potential evapotranspiration; however, they are not discussed here because the subject is covered in WMO *Technical Note* No. 83 (1966) which describes various approaches and contains many references to the large amount of work that has been done.

3.4.2 *Actual evapotranspiration* (AE) *methods*

Many of the previously mentioned problems of estimating actual evapotranspiration have been explored by Baier and Robertson (1966). Baier (1967) summarized the bulk of existing knowledge on the subject while presenting a method which has been found to produce fairly reliable results in Canada. Baier and his colleagues have also gone beyond the computation of soil water and have attempted to synthesize their work into a sort of index indicative of the agricultural implications of cumulative water deficits.

3.4.3 *Drought for spring wheat*

Mack and Ferguson (1968) illustrated the application of one of the soil-water accounting precedures to the problem of wheat yields in Canada. They summarized computed daily evapotranspiration deficits, $PE-AE$, during each of the six phenological periods for spring wheat in Manitoba over a 42-year period. Regression analysis showed grain yields reduced by an average of $311\ d_1 + 69.1\ d_2$ kg ha^{-1} where d_1 is the total evapotranspiration deficit, $PE-AE$, in cm from the fifth leaf stage to the soft dough stage and d_2 is cm of deficit from the soft dough stage to harvest. This derived measure of moisture stress or drought severity during these two growth periods accounted for 76 per cent of the wheat yield variability over a nine-year period.

In this case the accumulated *AE* deficit during particular growth periods constitutes a locally calibrated drought index. However, a given amount of *AE* deficit obviously has a different effect from one stage to another, as one would expect. The calibration of centimetres of water deficit in terms of kilograms per hectare of yield applies best to spring wheat at Brandon, Manitoba, under the cultural practices used there, but one would rather expect this measure of moisture stress to retain a good share of its applicability to spring wheat in other areas having a similar climate. It should be noted that this measure of water deficiency is in absolute terms; i.e., it expresses departure from potential evapotranspiration rather than from an average which is characteristic of the climate. If one is interested in actual crop yield, this absolute moisture deficit is the form that should be used for the drought index. However, in many instances the interest is in departures from normal or from trend yield (or production) in a number of areas. In this case the drought index must express the degree to which moisture has been either unusually deficient or unusually abundant. In other words, for areal comparability the index must express drought relative to the climatic averages. If this relative feature is omitted, the index is likely to reflect climate rather than weather.

3.4.4 *Drought for maize (corn)*

Another type of index, though again not universally applicable, should probably be mentioned because of the methodology used to develop it. Prior to the advent of water-balance accounting, Barger and Thom (1949) carried out a statistical analysis of 53 years of county corn-yield data and weekly rainfall data at six stations in Iowa (U.S.A.) and established drought threshold values for each station. These values represent the least amount of rain that occurred over any *n*-week period during the growing season without resulting in below average corn yields in more than 50 per cent of the years.

They assessed that the minimum rainfall required for normal corn development ranged from near zero at all six stations for a two-week period, parabolically upward week by week to a 16-week total of nearly 216 mm at some stations, but as much as 318 mm at others where the soils tend to be more limiting to water intake and root growth.

For a given season, *n*-week rainfall totals less than the established threshold amounts constitute agricultural drought having a severity, with respect to corn production, proportional to the magnitude of the rainfall deficiency. The largest single deficit regardless of duration is a measure of drought severity for that season.*

Even though separate drought threshold values are required for each crop at each station, the method is basically sound. The primary shortcomings are the neglect of soil water and water demand during a particular season. However, the mean values of these factors, as well as the average influence of the local soils, are taken into account during the development of the threshold values because the county corn-yield data have more or less integrated them. Perhaps if rainfall totals were replaced by computed total evapotranspiration deficits during the various *n*-week periods of the growing season, this approach to the establishment of a measure of drought severity might not require separate computations at each station.

3.4.5 *Moisture stress days*

Denmead and Shaw (1962) estimated turgor loss points for corn as a function of evapotranspiration at field capacity and root zone moisture. They found that corn plants lost turgor if potential evapotranspiration exceeded 6.4 mm per day when soil water was below 85 per cent of available capacity, *or* if *PE* exceeded 5.1 mm per day when soil water was below 50 per cent of capacity, *or* if *PE* exceeded 1.3 mm per day when soil water was less than ten per cent of available capacity.

Dale (1964) identified any day on which the combination of water demand and available soil water did not produce turgor loss according to the Denmead-Shaw concept as a non-stress day for corn. He found the cumulative total number of non-stress days during the critical period six weeks before to three weeks after the corn was 75 per cent silked to be a very good index of agricultural drought. As the number of non-stress days during this 63-day period decreased from about 30 to 11, corn yields decreased from near 6 350 kg per hectare to near 1 270 kg. In addition, an exceptionally favourable growing season, when the nine-week period produced 61 non-stress days, brought the yield up to 8 250 kg per hectare when stands were increased to 30 000 plants per hectare. Plant population appeared to have little influence on yield during drought years, i.e. during years when stress days were rather frequent.

Dale and Shaw (1965) later used the non-stress-day concept to develop a climatology of this index of agricultural drought in Iowa. Results were expressed in practical terms showing the soil water needed in the root zone or top 30 cm of soil at various times during the growing season to prevent moisture stress in corn for various levels of assumed risk. That is, to ensure moisture stress no more often than one year in ten at Ames, Iowa, the entire root zone or the top foot of Colo silty clay loam soils must be maintained at near 90 per cent of available capacity during the critical period. However, risking moisture stress occurrences in four years out of ten, these soils can be allowed to become considerably drier, but must still be maintained at no less than 80 per cent of available capacity during the most critical period.

Dale (1968) extended this climatological study of agricultural drought by an analysis of the frequency of occurrence of non-moisture stress days for corn during the critical nine-week period at a number of additional locations in Iowa. This measure of the probability of unfavourable weather for corn was compared with county corn-yield statistics for various areas. He found strong evidence that the variability of yields increases with increasing chances of moisture stress.

This soundly based measure of the severity of agricultural drought could very probably be generalized somewhat and could be modified to cover other crops.

**Note:* The drought threshold equation derived by Barger and Thom for south central Iowa, where the rainfall requirement was greatest during most periods, was $R = -15.2+9.27n+0.706n^2$, where R is rainfall in mm during a period of n weeks, for $1 \leqslant n \leqslant 16$. In central Iowa, where the rainfall requirements turned out to be least, the equation was $R = -15.3+6.29n+0.516n^2$, where R is rainfall in mm.

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3.4.6 *Drought and fire in vegetation*

One additional example represents another aspect of agricultural drought, that of drought as a problem in fire control in vegetation. The inflammability of vegetation depends largely on its moisture content. Although fires in bush, grass, and fields of standing or cut crops are of great concern, the problem of fire hazard and fire control has received greatest attention in connexion with forest fires.

Forest-fire control problems are intensified during drought which is sufficiently prolonged and severe that the deep duff and heavy fuels become dry. While a severe drought condition is not a prerequisite for the occurrence and spread of a fire, prolonged drought increases the intensity of fires that do occur and so increases the fire suppression problem.

The inflammability of forest fuels depends largely on their moisture content. In order to obtain a fire index, workers in this field have studied the meteorological factors which determine the rate of drying (WMO, 1961).

Direct assessments of fuel moisture state have often been made by using standard samples of forest litter and from this evolved the method of using a standard cylinder of wood, sometimes known as a hazard stick. The method is to expose in a standard manner one or more prepared sticks, usually about 1.25 cm in diameter and of known oven-dried weight. The moisture content of the sticks is weather-dependent and can be determined at any time by weighing. Variations are made in stick size and wood type to suit local purposes. Differences of opinion exist regarding the reliability of these sticks and it is fairly certain that they do not accurately represent the more rapidly fluctuating moisture content of lightweight fuels such as grasses and uncompacted dead leaves or the more stable moisture content of thicker branch and compacted debris. However, the method continues to have some application and for some areas continuous records of hazard stick "dryness" have been built up.

Meteorological methods of assessing fuel moisture state range from the use of single elements such as rainfall, temperature or humidity, usually plotted on a time scale, to sophisticated models integrating all factors affecting the drying of fuels. These complex approaches are closely related to evapotranspiration models. Streamflow has also been used as an indicator and although it reflects the integrated state of dryness of a catchment, the variations in flow from day to day are too small to provide a practical assessment of fire danger on a particular occasion. Rainfall is the principal source of fuel moisture but because of their hygroscopicity all dead fuels tend to approach a state of equilibrium with the moisture content of the air, depending on their dimensions. Moisture evaporates from fuels according to the well-known physical laws and thus the rate depends on the integrated effect of net radiation, temperature, humidity and wind speed. The rate of drying is near maximum at high moisture contents but decreases with decreasing moisture content. Hence a drought index has been incorporated in objective meteorological methods used to assess fire hazard. Soil water has very little effect on the moisture content of forest litter because there is no root system to draw on this reserve.

Most fire danger indices use some or all of the following meteorological elements to estimate fuel moisture content: air temperature; humidity; days since last rain; amount of last rain; and a vegetation parameter such as degree of curing of lesser vegetation.

The drought index developed for fire control purposes by Keetch and Byram (1968) is based on the assumption that for practical purposes, 200 mm represents the significant portion of the available water-holding capacity of the topsoil, deep duff and heavy fuels. The index ranges from 0 when the full 200 mm of water is present to 800 when the entire amount has been lost through evapotranspiration.

The index, I, is computed daily by the equations:

$$I_i = I_{i-1} - 3.94(P - 5.1) + E$$

where I_i is the index for today;
P is the rainfall in the past 24 hours in mm; and
$(P - 5.1)$ is set to zero for negative values.

If rain falls on two or more consecutive days, then for the second and subsequent days the threshold value of 5.1 mm is omitted and

$$I_i = I_{i-1} - 3.94\,P + E$$

The "drought factor" E for the current day is essentially an estimate of the water evaporated and transpired from the area during the current day. The value of this factor is read from tables which are calculated from an empirical equation:

$$E = \frac{(800-I+3.94P)\,(0.968\ \mathrm{e}^{\,0.0486(1.8T+32)} - 0.83)}{1000\,(1.0+10.88\ \mathrm{e}^{-0.00174R})}$$

where the first quantity in the numerator is limited to a range from 0 to 800; e = base of natural logarithms; T = maximum temperature during past 24 hours in °C; and R = normal annual precipitation for the area in mm.

It is assumed that R, the annual normal precipitation, is a measure of the type of climate and forest being considered; i.e., only 375 mm per year would support a rather sparse forest, but 1 750 mm per year would indicate a forest of near maximum density. For forests, this assumption may be fairly realistic, and it might also apply to some grasslands and some types of crop.

With a full supply of water, $I = 0$, one can regard E as potential evapotranspiration. This aspect is rather disconcerting inasmuch as the tables in the report show, for R = 1 750 mm, maximum E of only 0.5 mm per day with a maximum temperature of 10°C, but a surprising 23 mm per day with a maximum temperature of 42°C. Nevertheless, the equation reduces these maximum daily water-loss factors in proportion to the percentage of drying which has already occurred. Thus, potential evapotranspiration is reduced to actual evapotranspiration in accordance with a practice that has been used by others.

This measure of drought severity could be expected to work reasonably well in latitudes and climates similar to the south-eastern U.S.A., but it would require careful testing before being put to use in markedly different types of climates, primarily because the method for estimating maximum E seems to produce values which seem too large in humid regions and too small in arid to semi-arid regions.

3.4.7 *Drought in semi-arid pastoral areas*

Indices developed for agricultural and forest regions are often quite unrealistic when applied to arid and semi-arid areas where soil moisture rarely reaches field capacity and for a great deal of time may be close to wilting point. However, in spite of this classification of permanent drought on the basis of an agricultural index there is positive evidence that pastoral conditions may be sufficiently satisfactory to maintain an introduced animal population, admittedly of a very low density.

White (1955) considered that drought existed in the pastoral zone when one or all of the following conditions prevailed: pasturage becoming scarce, stock losing condition from fair order, hand-feeding in vogue, and agistment of stock.

Long-term records of observers' assessments of pasture and stock conditions were then examined and equated to rainfall. From this he was able to estimate the minimum critical amount of rainfall received in a specified period (e.g. 30 days) which started a green shoot after a drought period. This was defined as the initial effective rainfall and was mainly between 25 and 40 mm per month. He also found that in order to sustain growth over the following two months, approximately 70 per cent of the initial effective rainfall was needed each month. This was defined as the effective carry-over rainfall and for the areas under study these amounts ranged between approximately 18 and 25 mm per month.

Using the above criteria, White was able to assess the drought experience of a particular locality on the basis of rainfall and observer's comments on stock and pasture conditions. An anomaly arises in that apparently less rainfall is needed with decreasing annual rainfall and increasing evaporation but this may be explained by the fact that stock population decreases sharply towards the drier areas and it may be assumed that the quantity of feed available and consequent condition of stock are influenced by the stock population.

3.4.8 *Indices not specifically agricultural*

In addition to the indices of agricultural drought, a number of general drought indices have been developed. These are really indices of the degree to which the weather has been abnormally dry. They do not attempt to include the biological or engineering uncertainties which arise when one tries to derive an index which relates to the specific agricultural or hydrological effects of a period of abnormally dry weather. Even so, a general drought index, properly interpreted, can be very useful for agricultural purposes.

3.4.9 *Palmer drought index*

One of the more involved and, according to Julian and Fritts (1968), "the most satisfactory solution to the problem of combining precipitation and temperature as predictor variables" is the procedure developed by Palmer (1965). The Palmer index is universal in that persistently normal temperature and precipitation produce an index of zero in all seasons in all climates. Further, the extended period of greatest abnormal dryness of long record produces an index around −6, regardless of the degree of aridity or wetness of the climatic averages of the region being studied.

Results from the analysis of a long record provide a series of monthly drought-index values which, in general, range from around +6 to −6. The positive values are more or less incidental, but they do provide realistic measures of the degree of unusualness of extended periods of abnormally wet weather. The completed analysis breaks the meteorological record into separate periods of either drought, abnormally wet, or near normal. The following table lists the descriptive terms which have been assigned to describe the character of the weather represented by various intervals of the index.

Index	*Character of recent weather*
4.00 or more	Very much wetter than normal
3.00 to 3.99	Much wetter than normal
2.00 to 2.99	Moderately wetter than normal
1.00 to 1.99	Slightly wetter than normal
.50 to .99	Incipient wet spell
.49 to −.49	Near normal
−.50 to −.99	Incipient drought
−1.00 to −1.99	Mild drought
−2.00 to −2.99	Moderate drought
−3.00 to −3.99	Severe drought
−4.00 or less	Extreme drought

This procedure has been widely used in the U.S.A. and in some other areas of the world. Results are reported as being realistic in all areas. The procedure is mathematically simple, but it is involved and tedious. When done by hand, it is slow and time-consuming, but where computers are available, results can be attained quickly and

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rather inexpensively. The method is better suited for climatological analysis than for operational use. However, during periods when a major drought is developing and spreading, it affords a useful means for routinely assessing the areal distribution of the various degrees of drought severity. In the U.S.A. this is done on a weekly basis during critical situations (Palmer, 1968).*

3.4.10 *Foley drought index*

In order to examine the temporal pattern of wet and dry periods, the excesses or deficiencies of monthly (or other period) rainfall compared with the respective long-term average may be integrated to produce a graph of cumulated departures (sometimes called a residual mass curve). A succession of deficiencies may amount to a considerable total deficiency, thereby identifying a "drought" period. The graph has the advantage that it clearly shows both the duration and the amount of the rainfall deficiency. It has the disadvantage that all deficiencies carry the same weight irrespective of the water requirements of vegetation; and as these usually exhibit marked seasonal variations the indices are not always a true quantitative assessment of drought. Also, comparison of drought incidence and severity between stations having signficiant differences in average rainfall is not reliable. For example, two stations may have received the same rainfall in a particular month, but one, being normally wetter than the other, would experience a greater deficit; however, the inference of greater drought severity would not always be true. This can be overcome to some extent by dividing all values of monthly rainfall by the average annual rainfall. In the work of Foley (1957) deficiencies are expressed in thousandths of the annual rainfall, called "units" for brevity. Units are cumulated as a method of assessing a drought period and may also be divided by the number of months in a period to give an index of drought severity. This method of analysis has been used successfully in Australia in long-term drought studies and much of its success is due to the assumption that animal and plant husbandry are geared to the average rainfall in specific regions. An example of the index is shown in section 4.1.6.

3.5 **References**

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**Note:* For a detailed discussion of the calculations of the Palmer index see section 4.2.4.

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CHAPTER 4

METHODS OF ANALYSIS

4.1 Statistical analysis of rainfall data

4.1.1 *Data selection*

Before building up a sample of drought events it is necessary to select an objective definition of drought which suits the purpose of the investigation, having regard to the type of meteorological data available over the period of study and the subject area. Data should be uniformly derived in time and/or space, i.e. based on the same criteria, otherwise direct comparison may be misleading. Further, the choice of a suitable definition of drought is not always simple, as certain variables such as evapotranspiration may not be observed or are not available for the whole period or area.

Consistency should also be applied in determining the beginning and ending of a drought period but, as indicated in Chapter 1, this is often very difficult in view of the frequent uncertainty associated with these events. In particular, the beginning of drought is difficult to pin-point and even in retrospect often cannot be dated within two months.

Without the assistance of modern computing aids the simplest time periods for most studies are one day or one month, the usual period for which statistical means are calculated. However, where computers are available any period can be conveniently used.

4.1.2 *Normal rainfall*

There are several measures of central tendency, the most frequently used being the arithmetic mean followed by the median and the mode.

For a discrete distribution the *mean* $\bar{x}$ is given by $\bar{x} = \frac{1}{N}\sum f_i x_i$

where x_i is the value of the variable with frequency f_i and $N = \sum f_i$ is the total frequency. If the data are ungrouped,

$$\bar{x} = \frac{1}{N}\sum x_i .$$

The *median* is the quantile which divides the distribution into two equal parts. It is the middle value of a distribution.

The *mode* or modal class is the value or class with the largest frequency.

As indicated in Chapter 2, the "average" rainfall can be skilfully used to assess availability of water for the agriculture of a station. Years of experience give the good agriculturalist the ability to assess the characteristics of his local rainfall and he has learnt to adapt his land-use operations accordingly. He knows that years of above-average rainfall cannot be relied on to continue for long, that one dry year can be followed by another and then possibly by one even worse.

This approach is very subjective and, whilst it is certainly practical when backed by experience, it is not always reliable. Such an agriculturalist uses his memory as a crude method of assessing rainfall variability and obviously this can be improved upon by the application of orthodox statistical methods to long-term rainfall observations. These are discussed in the following subsections.

4.1.3 *Rainfall variability*

There are a number of useful measures of the dispersion of a frequency distribution but these will not be discussed here. The most common and useful measure is the standard deviation σ which for a normally distributed variate is the positive square root of the variance given by

$$\sigma^2 = \frac{1}{N} \sum (x_i - \bar{x})^2$$

or, in another form

$$\sigma^2 = \frac{1}{N} \sum x_i^2 - \bar{x}^2$$

or $$\sigma^2 = \frac{\Sigma x_i^2}{N} - \left(\frac{\Sigma x_i}{N}\right)^2 .$$

It can be shown that, for a normal distribution, 68 per cent of data lie in the range ± σ and 94 per cent of data lie in the range ± 2 σ.

As we are concerned here with droughts we can examine the low-rainfall end of the normal frequency distribution curve in greater detail. For example, we know that 16 per cent of occurrences in a normal distribution fall below the total $\bar{x} - \sigma$ and 3 per cent below $\bar{x} - 2\sigma$. As a first approximation we could regard these class ranges as containing occurrence of moderate drought and severe drought. An immediate advantage of this method is that occurrences can be allocated a return period or frequency.

Not all distributions are normal however and, in particular, rainfall may be significantly different from normal especially for periods of a month or less. Under these conditions it is not appropriate to use the standard deviation. Other measures of dispersion, such as the interquartile range, may still be used but these are less suitable for statistical application.

Skewness, or the degree of asymmetry of a distribution, is also significant in drought studies. The skewness of a distribution is given by

$$\gamma_1 = \frac{\Sigma (x_i - \bar{x})^3}{N \sigma^3}$$

For a normal distribution $\gamma_1 = 0$. If γ_1 is positive the distribution is said to show positive skewness and the longer tail of the curve is to the right; under these circumstances a station would experience a lower level of rainfall more frequently than indicated by the normal distribution.

4.1.4 *Frequency distribution*

Another method of showing the dispersion of a sample is to present data in a frequency array showing frequencies of occurrence either in graphical form (the cumulative frequency curve) or as a table showing frequencies of occurrence in specific class intervals or ranges. The method has the advantage that it does not depend on the normality of the distribution.

Cumulative frequency curves or tables are particularly useful when comparing rainfall frequencies at different stations or different months or other intervals at the same station. For example, a station with a high mean and marked variability may experience some low-level total with the same frequency as a station with a lower mean and variability.

4.1.5 *Deciles of rainfall*

These are one particular example of the application of cumulated frequency distributions. In this method the limits of each decile of the distribution are calculated from a cumulated frequency curve or an array of the data. Thus the first decile is that rainfall amount which is not exceeded by the lowest 10 per cent of totals, the second decile is the amount not exceeded by 20 per cent of totals and so on. The fifth decile or median is the rainfall amount not exceeded on 50 per cent of occasions. The decile ranges are the ranges of values between deciles, thus the eighth decile range is that between deciles seven and eight.

The values of the deciles give a reasonably complete picture of a particular rainfall distribution and knowledge of the decile range into which a particular total falls gives useful information on departure from normal. The following descriptions of decile ranges are useful in classifying rainfall occurrences:

Very much above normal	Highest 10 per cent	Decile range 10
Much above normal	80 to 90 per cent	Decile range 9
Above normal	70 to 80 per cent	Decile range 8
Slightly above normal	60 to 70 per cent	Decile range 7
Normal	Middle 20 per cent	Decile ranges 5 and 6
Slightly below normal	30 to 40 per cent	Decile range 4
Below normal	20 to 30 per cent	Decile range 3
Much below normal	10 to 20 per cent	Decile range 2
Very much below normal	Lowest 10 per cent	Decile range 1

TABLE III

Rainfall frequency data for Buenos Aires, expressed in decile values, 1861-1968: 108 years
(Rainfall in mm)

Decile	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
Lowest	3		2	5	0	1			3	4	12	5	504
1	19	17	31	21	11	13	9	14	19	24	28	30	701
3	50	49	59	54	34	34	29	33	40	54	53	58	848
5	76	68	101	82	61	56	49	52	63	77	81	82	940
7	108	95	149	111	97	81	71	80	102	104	102	113	1069
9	15	152	217	165	167	128	113	140	148	185	159	164	1284
Highest	348	249	545	405	245	174	212	278	349	367	284	318	2023

Table III is an example of decile analysis for Buenos Aires. This shows deciles 1, 3, 5, 7 and 9 for each month together with the highest and lowest rainfall totals on record. Table IV shows first, fifth and ninth decile values of rainfall cumulated in monthly sequences of one to twelve and commencing in each month of the year. For example, the median value of the six months' rainfall from April to September is 408 mm but in 10 per cent of years the total for this period may be 263 mm or less. The table is very useful when dealing with a particular crop since when the growing season and moisture requirement are applied, some idea of the drought risk is obtained.

TABLE IV

Details of rainfall experienced in consecutive months commencing with the month indicated.
Buenos Aires, 1861-1968: 108 years
(Rainfall in mm)

Decile No.	*No. of months*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
1	1	19	17	32	21	11	13	9	14	19	24	28	30
	2	61	81	96	72	49	44	37	52	80	88	77	78
	3	156	151	140	100	88	76	102	121	140	142	139	131
	4	214	197	190	148	139	153	161	188	198	192	201	201
	5	269	240	224	199	199	203	225	240	274	261	265	296
	6	311	282	279	263	265	283	286	333	318	349	359	350
	7	367	346	349	328	322	358	368	405	406	423	424	414
	8	403	410	408	394	395	423	426	474	476	480	479	460
	9	465	489	486	471	470	479	494	543	546	552	527	499
	10	560	566	554	543	533	559	571	589	615	595	548	553
	11	629	639	639	598	614	636	647	665	655	621	612	643
	12	706	711	705	687	683	700	692	713	701	705	695	710
5	1	76	68	101	82	61	56	49	52	63	77	81	82
	2	155	182	189	154	133	109	107	133	144	161	168	174
	3	262	271	262	220	175	176	182	219	242	251	262	259
	4	343	339	336	275	238	243	271	292	341	340	345	343
	5	420	399	376	326	329	327	355	392	419	420	434	435
	6	486	468	428	408	413	415	439	466	497	527	529	508
	7	537	511	505	490	507	498	528	544	604	622	589	571
	8	592	581	592	590	584	581	611	667	685	677	647	629
	9	679	668	685	684	663	646	724	747	770	739	713	679
	10	764	755	789	767	738	782	799	815	806	792	756	780
	11	840	849	868	848	869	873	876	878	890	878	870	851
	12	935	955	949	966	954	931	930	927	924	939	934	931
9	1	151	152	217	165	167	128	113	140	148	185	159	164
	2	291	288	339	271	243	210	208	237	283	312	314	294
	3	445	408	442	364	316	308	307	377	396	428	413	387
	4	581	540	525	431	388	406	458	510	533	527	510	563
	5	656	618	601	503	489	575	566	628	608	620	661	692
	6	746	678	668	569	641	659	677	704	718	764	794	772
	7	808	732	778	727	740	775	781	790	840	856	878	840
	8	870	861	885	839	860	896	878	942	975	1008	954	904
	9	954	976	978	959	950	951	1021	1065	1075	1055	993	976
	10	1073	1060	1114	1066	1037	1101	1147	1185	1129	1103	1060	1091
	11	1167	1188	1233	1139	1243	1253	1217	1229	1174	1181	1153	1190
	12	1284	1310	1293	1310	1359	1295	1306	1244	1233	1251	1263	1270

Gibbs and Maher (1967) have used this concept to study Australian droughts. Maps have been prepared based on more than 80 years of record showing the decile ranges in which rainfall for each year has occurred. By delineating the various decile values the gradation from very dry through average to wet conditions are shown. Consecutive years in which drought by this definition covered relatively large areas of Australia during the period 1960 to 1965 inclusive are shown in Figure 2.

Table V shows in chronological order the year in which the first decile range covered more than ten per cent of the continent.

In several years large proportions (over 50 per cent) of the area of individual States received rainfall in the first decile range but on each occasion there were other States, or large parts thereof, where better rainfall was received. Gibbs and Maher therefore conclude that "drought" affecting the whole of Australia is virtually impossible

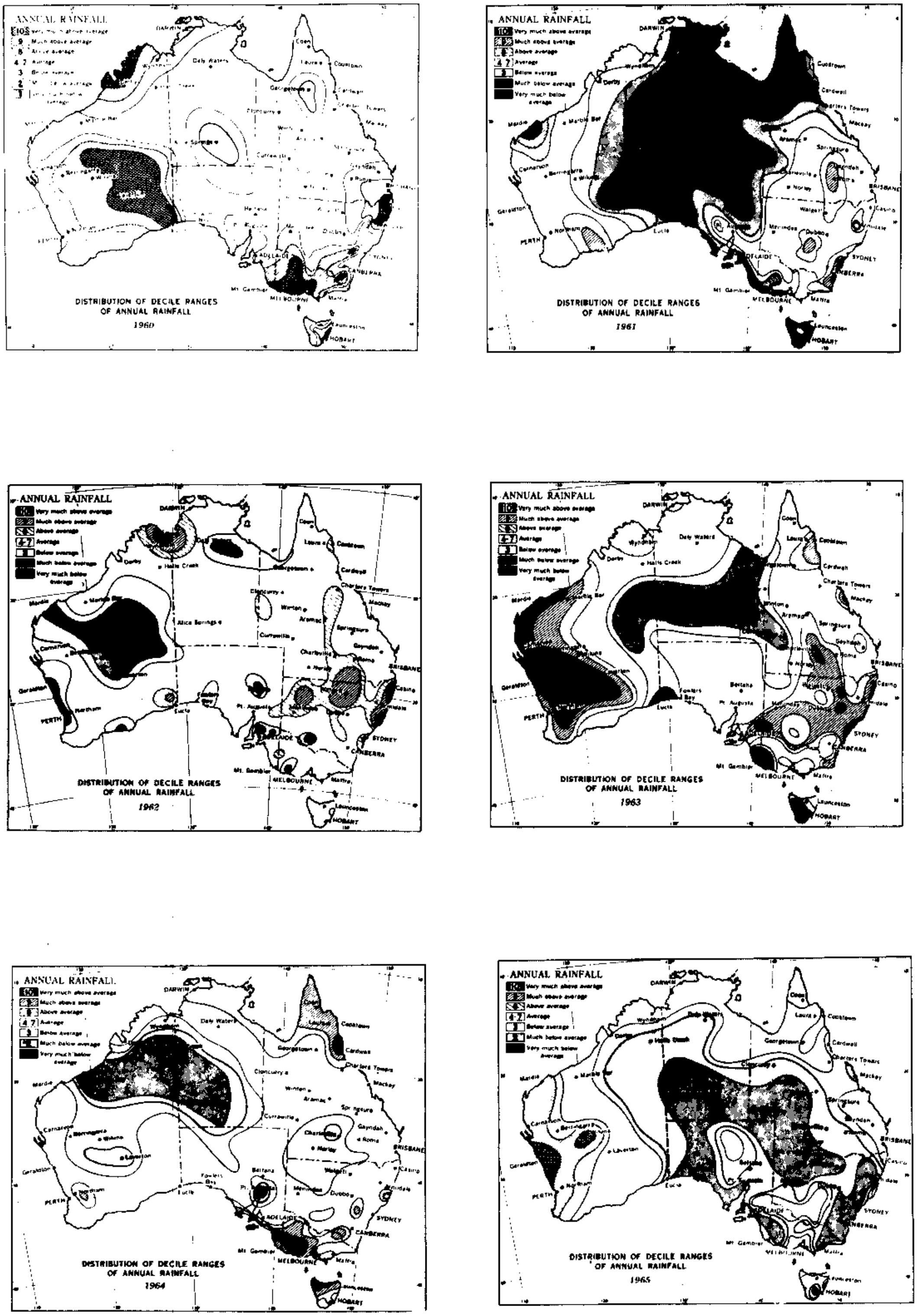

Figure 2 – Drought areas over Australia in each of the years 1960-1965 expressed in decile ranges of rainfall

TABLE V

Per cent of area of Australia having annual rainfall in first decile range (≤ 10 %) (based on period 1885-1969)

Year	*Per cent of area*	*Year*	*Per cent of area*	*Year*	*Per cent of area*	*Year*	*Per cent of area*
1888	17	1914	15	1928	43	1958	14
1891	19	1915	19	1929	29	1959	13
1892	11	1918	13	1935	23	1961	46
1894	12	1919	23	1936	22	1963	11
1897	33	1923	11	1940	34	1964	17
1900	17	1924	21	1944	27	1965	22
1902	32	1926	15	1952	22		
1905	33	1927	25	1957	14		

and that "drought" over half the continent might be expected about once in fifty years. During the same period, ten or eleven years almost completely free of drought might be expected. A weakness of the method is that all drought periods within a continental area are not coincident in time, i.e., there may be two or more apparently independent droughts with different dates of beginning and ending, either of which may be outside the specified time period; thus the decile procedure does not always give the full temporal picture of a drought.

4.1.6 *Temporal display of data*

Most drought statistics can be plotted on a time base to show subjectively variations in the values. The simplest form is rainfall itself but most parameters or drought indices shown in Appendix I are adaptable to this procedure.

A variation from this method is to plot departures from a central value such as the arithmetic mean, cumulated values of indices, or their departure from normal.

Figure 3 shows a number of selected indices plotted on a common time base. The method has the advantage of showing up clearly extended periods of drought or absence of drought and if a reference line can be incorporated in the diagram, some measure of intensity can be obtained. The various indices in Figure 3 tend to follow one another rather closely but this does not confirm their value as reliable indices unless they can be compared with some more absolute standard such as available water in the soil or crop state.

A very useful example of the temporal presentation of drought data is the method used by Foley (1957). This is a variation of the residual mass curve in which departures of rainfall from average for each specified period, e.g. monthly, are cumulated. Foley divides each monthly anomaly by the average annual rainfall, then divides by 1000, and cumulates the dimensionless "units" so obtained. Figure 4 is an example of a drought analysis by this method. (For further discussion see section 3.4.10.)

4.1.7 *Frequency of drought in sequences*

The simple tabular presentation of monthly rainfall data can be extended to show frequencies of periods during which each monthly total was less than an amount specified for that month. If each month of a long rainfall record is compared with a drought criterion a number of drought periods of various durations will be apparent and these may be summarized to indicate their frequencies of occurrence.

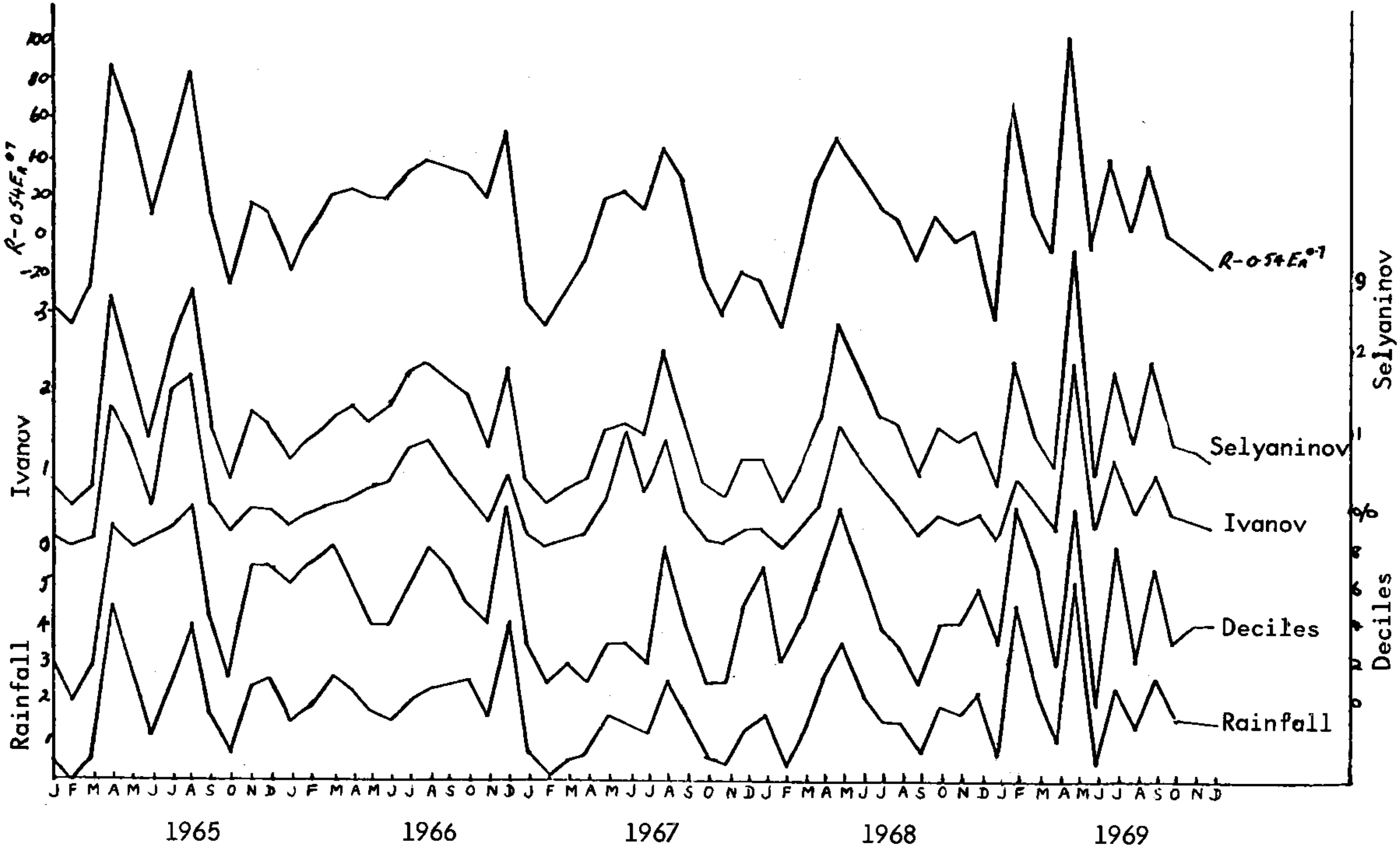

Figure 3 – Temporal presentation of drought data for Melbourne

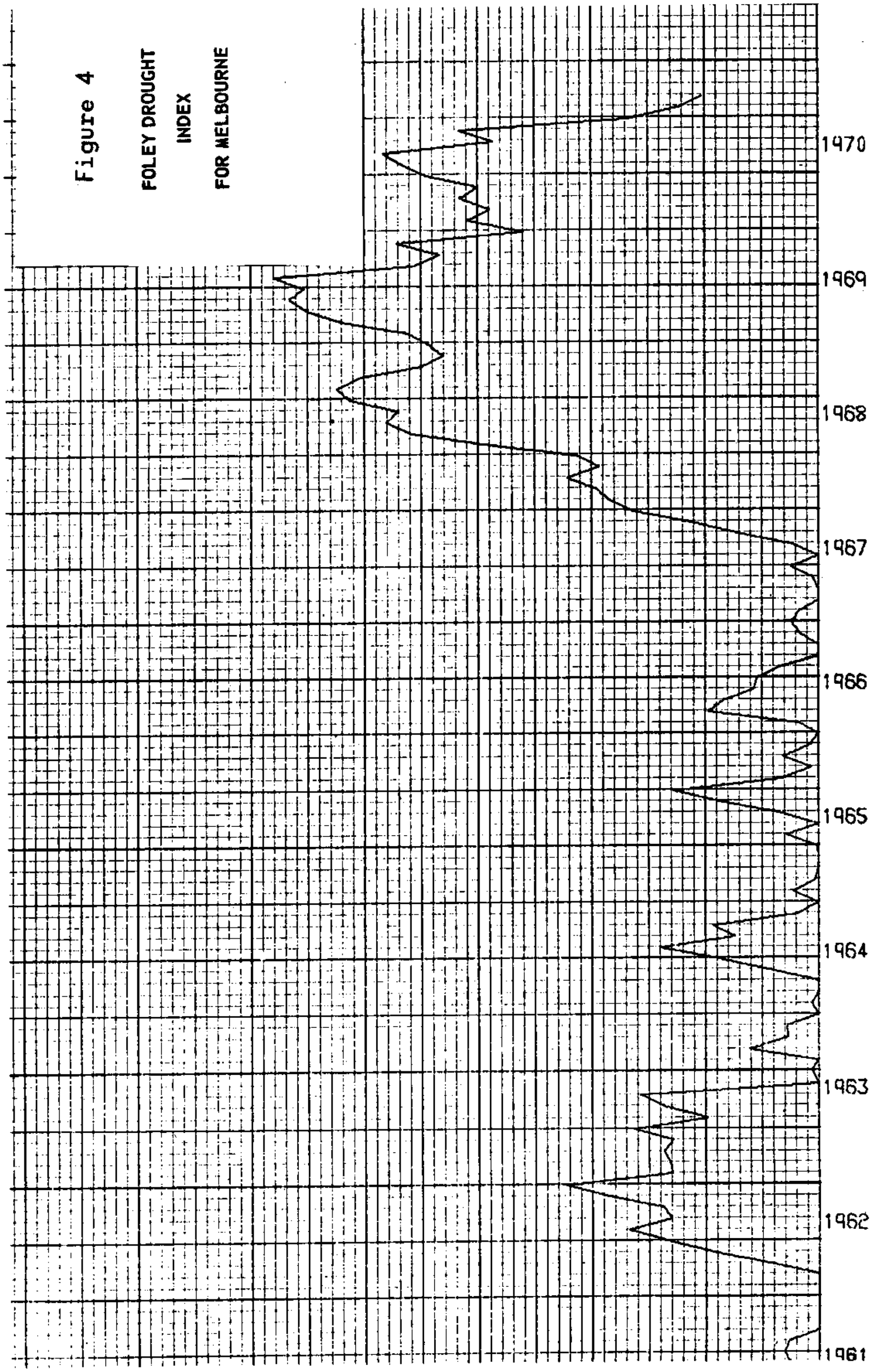
Figure 4 FOLEY DROUGHT INDEX FOR MELBOURNE

In the example given in Tables VI and VII, non-effective rainfall is defined as occurring when rainfall P is less than $1.43\ E^{0.7}$ where E is Australian tank evaporation (both P and E in mm) and exhibits a marked seasonal variation. Occurrences may be summarized (Table VI) as the percentage number per month when rainfall was less than the critical amount (i.e. non-effective) or the lengths of periods of sub-critical rainfall can be summated to show the frequencies of drought periods of various duration, commencing in each month of the year (Table VII).

TABLE VI

Frequency of non-effective rainfall by months at Rainbow (Australia) (per cent)

Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
91	84	89	70	37	20	16	26	40	65	81	87

TABLE VII

Frequency of occurrence of periods of non-effective rainfall at Rainbow (Australia) (per cent)

Non-effective rainfall for	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
2 months	80	80	67	29	4	2	8	16	31	52	69	73
3	76	59	25	2		2	6	12	29	50	66	60
4	55	21	2				6	12	27	44	53	56
5	17	2					6	10	23	31	48	39
6	2						4	8	17	29	33	6
7							4	6	15	25	4	
8							4	6	15	4		
9							4	6				
10							4					

Table VII shows that the months January and February were consecutively droughty on 80 per cent of occasions, January-March on 76 per cent, January-April on 55 per cent, January-May on 17 per cent and January-June on 2 per cent. October was droughty in 65 per cent of years (Table VI) and in more than half of these the drought continued for at least four months, 44 per cent of years (Table VII). In 25 per cent of years drought which commenced in October continued for at least seven months.

Although monthly totals of rainfall have certain advantages, this type of table can be constructed for other periods of rainfall data. It is also readily adaptable to other drought indices where the condition of drought or no drought is specified as the basic data rather than actual rainfall amounts or departures from a mean. Thus it does not present a measure of the intensity of drought.

4.1.8 *Persistence*

Runs of rainfall may be considered in terms of any convenient number of days or weeks and the question is raised whether the occurrence of runs with certain expectancies is consistent with a hypothesis of completely random distribution.

Brooks and Carruthers (1953) consider the case of the expected number of runs by occurrences of events which either can or cannot occur in a series free from persistence. In such a series the probability p that an event will occur and the probability q that it will not occur ($p + q = 1$) are independent of preceding events. The average length of a run is calculated to be $\frac{1}{1-p}$ and is a maximum of 2 when $p = q = 0.5$.

To test this the number of runs of monthly rainfall equal to or greater than the median value have been calculated and these frequencies compared with the observed (Table VIII).

TABLE VIII

Number of runs of monthly rainfall equal to or less than the median value ($p = 0.5$) at Condoblin (Australia) (1881-1964)

Length of run (months)	*2*	*3*	*4*	*5*	*6*	*7 or more*	*Total*
Expected	126	63	31	16	8	8	252
Observed	108	53	38	9	11	14	233

It will be seen that two- and three-month observed runs were about 15 per cent less than predicted whereas the six- and seven-or-more-month runs occurred considerably more frequently than expected. Compared with expected values the effect is to decrease the number of short runs and increase the number of long runs; the total number of runs is also slightly less than the expected.

The reasons for persistence are not fully understood but work in this field would be very rewarding if trends such as the continuation of drought could be predicted.

4.1.9 *Extreme values*

If it can be shown that the rainfall sample is normally distributed, then it is possible to extrapolate the cumulated distribution to obtain estimates of drought frequency at the lower end of the range. For example, from 50 years of record it is possible to estimate with reasonable accuracy the rainfall amount with a return period of 100 or perhaps even 200 years, although the method becomes too unreliable when used to estimate greater extremes.

The method may be applied either as a strict statistical exercise on which confidence limits of the estimates can also be calculated, or, as is often done, data may be plotted on probability paper, and, if normality tests are satisfied, the curve extrapolated and values simply read off.

It is often possible to overcome difficulties due to the lack of normality of a sample distribution by effecting a transformation to another form. For example, it is often found that monthly rainfall data are not normally distributed but that the square roots of the same data are. In dealing with heavy rainfall values such as maximum falls per year, it is often found that the logarithms of these falls are normally distributed.

Departure from normality of rainfall tends to increase with decreasing time interval. Monthly rainfall totals generally exhibit greater departures than annual whilst daily rainfall totals are even more skewed. Daily totals are extremely skewed in arid zones where a high proportion of totals, perhaps in excess of 90 per cent, are zero and because of this there is no normalizing transformation. The gamma distribution has been used effectively on samples of this type to provide solutions concerned with the incidence of abnormally high rainfalls, the obverse of drought.

A variety of extreme-value theories have been in use in the last 20 to 30 years following the work of Pearson, Gumbel and others but these will not be discussed here. In the *Technical Note* "Estimation of maximum floods" (WMO, 1969) there is a chapter dealing with extreme values. Although the discussion pertains to high extremes some of the theory and applications might be applied to the obverse (droughts).

4.1.10 *Spatial correlation*

As indicated in Chapter 1, spatial correlations have been carried out in the United States (Yevjevich, 1967) and these lead to some interesting conclusions on the areal extent of drought.

In applying this statistical technique it is necessary first to test the normality of the different rainfall samples to be correlated and if these are significantly different from normal a transformation procedure should be applied.

Maher (1968) studied the spatial association of rainfall over Australia using 100 stations for the period 1900-1964. Selecting each station in turn, correlation coefficients were calculated with each of the other stations to determine the degree of correlation between annual rainfalls. Taking a null hypothesis that the population value of the correlation coefficient, r, is not zero it was shown that the five-per-cent significance value of r is 0.25, based on 68 pairs of rainfall totals.

Isopleths were drawn relative to each station and Figure 5 shows the pattern using Alice Springs, in the centre of Australia, as the master station. There is a significant correlation between annual rainfalls in the climatic zone centred on the master station but no correlation at all between rainfall at the master station and in the eastern and western quarters of the continent. Apart from the high correlation around the master station the patterns for other stations also show a general west-north-west to east-south-east configuration which is probably associated with the normal paths of moving synoptic systems. Yevjevich (1967) also noted that correlation patterns did not form circles as might be expected but were approximated by ellipses. He states however that the orientations of the axes of maximum and minimum correlations do not afford a ready means of tracing the flux of atmospheric moisture or a means of identifying its sources.

Maher (1968) suggested the computation of correlation coefficients to years when rainfall at the master station was below the median value, i.e. treating half the number of years of record. From such a study it should be possible to evaluate the degree and pattern of rainfall association when conditions are dry at the master station.

4.2 **Water-balance methods**

4.2.1 *Introduction*

Application of the water-balance equation to drought was discussed in Chapter 1 and the following paragraphs give some details regarding the use of some selected models. All methods use the same basic equation:

$$P - Q - U - E - \Delta W = 0$$

where P is the precipitation or irrigation water;

Q is runoff;

U is deep drainage passing beyond the root zone;

E is evapotranspiration;

ΔW is change in soil-water storage.

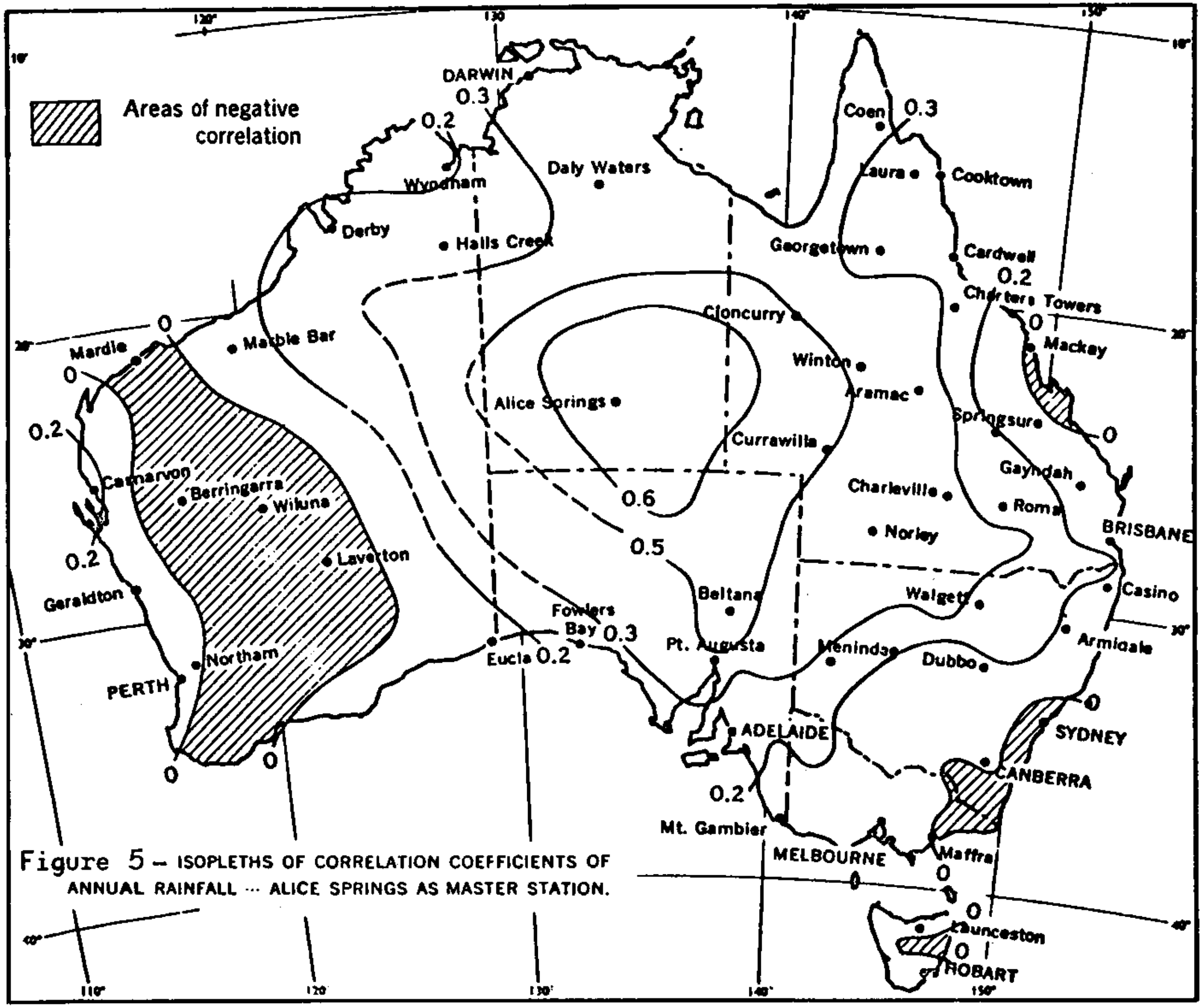

Figure 5 – ISOPLETHS OF CORRELATION COEFFICIENTS OF ANNUAL RAINFALL … ALICE SPRINGS AS MASTER STATION.

Each of the terms in this equation has special problems associated with its measurement or estimation. Fortunately the procedure is simplified considerably in the case of drought studies, as P, Q and U become negligible quantities, so that the problem areas are reduced to evapotranspiration and the availability of soil water. This simplification is often more apparent than real however, mainly because of the difficulty in estimating evapotranspiration under conditions of soil drying. The main differences between models used in drought studies are the assumptions made regarding soil-water storage and the related process of infiltration, and the rate of evapotranspiration and its dependence on soil-water content.

Numerous expressions have been proposed to estimate the infiltration rate, that is, the rate at which the soil-water store is recharged. These usually assume that, for a particular soil type, the mass of water infiltrated is either proportional to time or is some function of time and water content (other factors such as permeability or surface soil conditions are specified by a particular soil). A number of water-storage zones in the soil profile may be postulated from which is drawn water for transpiration, and an efficient model should compute the passage of infiltrated water from one level to the next lower one, and of deep percolation to groundwater store where it plays no further part in the local water balance.

However, most practical water-balance models ignore the details of infiltration processes and assume that soil-water storage is always replenished provided adequate water is available at the surface. Fortunately infiltration is minimized during drought periods.

Some methods of water-balance accounting use a single measure of water storage or water deficiency (capacity minus storage) whilst others are far more complex, with variable water capacity and multi-level storage.

Kohler (1963) describes a multi-capacity soil-water accounting system in which a catchment is subdivided into five sections, each having different water-holding capacity, based on vegetation, soils and physical characteristics of the catchment. If two-level accounting is carried out for each of several assumed capacities, then computation becomes rather complex and can be handled adequately only by electronic computers.

Evapotranspiration raises difficult problems in water-balance studies, particularly in the assessment of drought, because of uncertain knowledge regarding the rate of loss during the drying cycle of soil. A number of methods for estimating evaporation are available, most of which give potential evapotranspiration; those which claim to give actual evapotranspiration are generally more complex and unreliable. These have recently been summarized by Hounam (1971) with particular reference to problems in water-balance studies.

The following concepts describing the extraction of water from the soil by plants have been used in the last 30 years in the development of water-balance models:

(a) Evapotranspiration independent of soil water: Transpiration takes place at the maximum rate over the full range of soil-water content. This simple approach is readily adaptable to modelling but it cannot be reliably applied to most conditions of soil and plant growth or of the environment.

(b) Evapotranspiration potential, reducing in very dry soil: This model assumes maximum transpiration except in very dry soil. A practical application of this method assumes transpiration at 90 per cent of the potential rate until two-thirds of the available water is exhausted. A variation of this method is used by Penman (1963), who assumes that plants transpire all water from the "root zone", plus one inch of water drawn from below this level, at the potential rate. When this supply is exhausted, transpiration is reduced to one-tenth of the potential rate.

(c) Evapotranspiration linearly proportional to soil water: This model has been used by a number of workers, notably Thornthwaite and Mather (1955), under conditions of high evaporative demand.

(d) Evapotranspiration decreasing exponentially: Numerous models of this type have been developed showing a wide variation according to vegetation and soil type and possibly also season as root density and canopy change (Baier and Robertson, 1966). Some models incorporate periods, when water content is high, during which evapotranspiration is at the potential rate; thereafter exponential decay takes over. The simple Antecedent Precipitation Index (API), used in some flood-forecasting techniques to assess the water status of a catchment, is a good example of exponential drying.

(e) Multi-level models: In its simplest form (Kohler, 1963) water storage is separated into two levels, the "upper level", which contains most of the plant roots, and the "lower level", which contains fewer roots. Water in the "upper" zone is depleted at the potential rate and any deficiency in this zone must be satisfied by rainfall before recharge of the lower zone commences. Depletion from the lower zone occurs only when there is no water available in the upper zone, the rate of evapotranspiration being proportional to the amount of water available in the lower zone. Models employing more than two layers have been proposed by Holmes and Robertson (1959) and Baier and Robertson (1966).

It is not surprising that a large number of models describing the water balance are available and these vary mainly in the way in which they handle the evapotranspiration and soil-water storage terms. This is best illustrated by a number of examples and the following sections describe some of the more popular procedures. The selection is not exhaustive nor is it intended to recommend strongly the use of these models rather than others not described. The examples are intended to give a broad picture of the variety of models and the way in which they may be used.

4.2.2 *Thornthwaite method*

The Thornthwaite model of the water balance, which may be used on a daily or long-period basis, has been applied to the solution of numerous soil-water problems, including the study of agricultural drought (Mather, 1961).

The model takes the difference between precipitation and evapotranspiration and carries forward a balance of water deficiency or surplus. A first requirement is the water-holding capacity of the soil relative to soil type and land use, and these are tabulated by Mather for a wide range of conditions. Water surplus can be readily computed and is considered as drainage and runoff. Water deficiency is more difficult to compute because actual evapotranspiration is assumed to vary with the water content of the soil and, in the Thornthwaite model, the rate of evapotranspiration is computed from the precipitation with reference to the amount of available water remaining in the soil (Thornthwaite and Mather, 1955). When precipitation is less than the potential evapotranspiration, the actual evapotranspiration equals the precipitation plus any soil water which is evaporated or transpired. (The latter is the soil-water storage change.)

In the work of Thornthwaite and his associates, potential evapotranspiration has been computed from the mean temperature by the well-known Thornthwaite (1948) technique. However, the model is equally suitable for any of the methods of estimating evapotranspiration.

For a more detailed explanation of the application of the model see Mather (1961), where sample computations are presented. The same reference includes reports by Pengra on the use of a mechanical-type calculator (IBM 602) and by Engelbrecht, using an electronic computer (IBM 650).

Table IX, taken from Mather (1961), is an example of a water-balance computation for Auburn, Alabama. The first section of the table shows computations based on average values of precipitation and evapotranspiration and an average period of deficient rainfall of five months from May to September is indicated. However, in the individual years 1933 and 1934 used as examples the number of dry months were seven and five respectively.

Mather also compares the results of computations using daily and monthly values of precipitation and evapotranspiration. He concludes that the use of monthly data gives values of both surplus and deficit that are too

TABLE IX

Climatic water balances, Auburn, Alabama. Long-term average and for years 1933, 1934
(all values in cm)

Av.	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
PE	1.4	2.0	3.7	6.9	11.1	14.6	16.3	15.2	11.7	6.7	3.0	1.5	94.1
P	12.4	13.8	14.9	10.5	9.1	10.6	13.9	11.6	8.0	7.2	8.8	13.1	133.9
Δ	11.0	11.8	11.2	3.6	−2.0	−4.0	−2.4	−3.6	−3.7	0.5	5.8	11.6	+39.8
$\Sigma\Delta$					−2.0	−6.0	−8.4	−12.0	−15.7				
ΔST	0	0	0	0	−2.0	−3.5	−1.9	−2.6	−2.3	+0.5	+5.8	+6.0	
ST	30.0	30.0	30.0	30.0	28.0	24.5	22.6	20.0	17.7	18.2	24.0	30.0	
AE	1.4	2.0	3.7	6.9	11.1	14.1	15.8	14.2	10.3	6.7	3.0	1.5	90.7
D	0	0	0	0	0	0.5	0.5	1.0	1.4	0	0	0	3.4
S	11.0	11.8	11.2	3.6	0	0	0	0	0	0	0	5.6	43.2
1933													
PE	2.9	1.9	3.9	6.3	14.5	16.4	16.6	16.2	14.1	8.0	3.3	3.6	107.7
P	6.5	16.7	18.8	5.8	3.4	5.9	8.2	8.9	8.7	10.6	2.8	5.0	101.3
Δ	3.6	14.8	14.9	−0.5	−11.1	−10.5	−8.4	−7.3	−5.4	2.6	−0.5	1.4	−6.4
$\Sigma\Delta$				−0.5	−11.6	−22.1	−30.5	−37.8	−43.2	(−33.9)	−34.4		
ΔST	0	0	0	−0.5	−9.2	−6.0	−3.5	−2.4	−1.4	+2.6	−0.2	+1.4	
ST	30.0	30.0	30.0	29.5	20.3	14.3	10.8	8.4	7.0	9.6	9.4	10.8	
AE	2.9	1.9	3.9	6.3	12.6	11.9	11.7	11.3	10.1	8.0	3.0	3.6	87.2
D	0	0	0	0	1.9	4.5	4.9	4.9	4.0	0	0.3	0	20.5
S	3.6	14.8	14.9	0	0	0	0	0	0	0	0	0	33.3
1934													
PE	2.1	1.3	3.7	7.2	11.6	16.6	18.0	16.0	12.2	8.0	4.2	1.5	102.4
P	4.5	10.8	9.1	9.6	9.2	13.2	7.9	16.0	4.2	12.2	6.4	5.7	108.8
Δ	2.4	9.5	5.4	2.4	−2.4	−3.4	−10.1	0	−8.0	4.2	2.2	4.2	6.4
$\Sigma\Delta$					−2.4	−5.8	−15.9	−15.9	−23.9				
ΔST	+2.4	+9.5	+5.4	+1.9	−2.3	−3.0	−7.1	0	−4.2	+4.2	+2.2	+4.2	
ST	13.2	22.7	28.1	30.0	27.7	24.7	17.6	17.6	13.4	17.6	19.8	24.0	
AE	2.1	1.3	3.7	7.2	11.5	16.2	15.0	16.0	8.4	8.0	4.2	1.5	95.1
D	0	0	0	0	0.1	0.4	3.0	0	3.8	0	0	0	7.3
S	0	0	0	0.5	0	0	0	0	0	0	0	0	0.5

PE = potential evapotranspiration; P = precipitation; $\Delta = P-PE$; ΔST = change in storage; ST = soil water storage; AE = actual evapotranspiration; D = water deficit; S = water surplus.

small. Water deficits are also underestimated when computations are based on average monthly values. For two stations in the United States deficits on a monthly basis were over 50 per cent less than when computed on a daily basis whilst deficits computed from average values were so much less as to be unrealistic.

The Thornthwaite model has been used to assess the feasibility of irrigation as it provides information on the total volume of water needed at any time and gives a definitive measure of drought. When compared with the water surplus in other seasons it shows whether there is enough water present during the year to permit irrigation. At the same time determination of the changes in soil-water storage on a daily basis gives information on the state of soil water at any time for use in the scheduling of the time and amount of irrigation to avoid the occurrence of any drought which will limit agricultural yields.

4.2.3 *Fitzpatrick method*

This uses the generalized water-balance model to assess the duration of plant growth as governed by the availability of soil water and can therefore be used in drought studies by reference to periods of water deficiency.

In a study of climate in relation to cropping and pasture Fitzpatrick (1965) makes the following assumptions:

(a) Rainfalls over weekly intervals contribute to the recharge of available soil-water storage up to a maximum of 10 cm. After this assumed limit has been satisfied, all additional rainfall is considered as excess and is lost either through surface runoff or deep percolation;

(b) The evapotranspiration rate for any week is proportional to the evaporation from the Australian sunken tank evaporimeter;

(c) If the estimated soil-water storage plus current weekly rainfall exceeds 64 mm, evapotranspiration proceeds at the potential rate. In this particular model this is computed as 0.8 times the tank evaporation (see *(b)* above).

(d) If the estimated soil water plus current weekly rainfall is less than 64 mm, evapotranspiration rate is computed as 0.4 times tank evaporation. This is a generalization of the decline in actual evapotranspiration as available soil water reserves are depleted.

These criteria do not take account of reduced evaporative losses resulting from special cultural practices, such as bare fallowing, which are likely to occur prior to crops forming complete ground cover or when they have passed into physiologically less active stages. Several models incorporating these factors have been developed but their use is limited as they are restricted to the conditions for which they were derived.

The model has been used by Fitzpatrick to compute the numbers of weeks during each year that soil water was within the available range (0-10 cm), i.e. periods when native pastures would be expected to make useful growth. It is a simple matter to invert such computations to indicate periods of limited or zero growth.

4.2.4 *Palmer method*

The Palmer index model was discussed generally in section 3.4.9. Briefly, the method requires a climatological analysis of a long record in order to derive five constants which define certain moisture characteristics of the climate of the area of interest. The first step requires a month-by-month water-balance accounting for a long record, such as 30 years or more. Palmer used a two-layer soil model and the Thornthwaite method of computing potential evapotranspiration. However, the methodology does not require any particular method of computing PE. Potential values were also derived for runoff, moisture recharge and moisture loss.

Next, the results of the water-balance accounting must be summarized so as to produce the five constants for each of the 12 calendar months. One constant, α, is the coefficient of evapotranspiration, the ratio of the computed mean monthly evapotranspiration (ET) to the mean monthly potential evapotranspiration (PE). This ratio is near 1.0 in humid climates, but approaches zero in very arid regions. Another constant, β, the coefficient of recharge, is the ratio of the mean monthly moisture gain (R) to the mean maximum possible gain (PR). The coefficient of loss, δ, is the ratio of mean moisture loss (L) to mean potential loss (PL), where potential loss is the amount of evapotranspiration that would have occurred if no precipitation had fallen during the month. The coefficient of runoff, γ, is the ratio of computed mean runoff (RO) to mean potential runoff (PRO)*. The last constant, K**, is an empirically derived weighting factor which depends on a number of measures of the moisture supply and demand characteristic of the climate in question.

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* Palmer used PRO = available water capacity $- PR$, but indicated PRO could be defined as $3\bar{P} - PR$.

** $K = 448.8\ \underline{K'/\bar{D}K'}$

where $\bar{D} = |P - \hat{P}|$,

$\hat{P}$ is an adjusted value of the precipitation which is Climatically Appropriate for Existing Conditions (CAFEC), and

$$K' = 1.5 \log_{10}\left[\left(\frac{\overline{PE} + \bar{R} + \overline{RO}}{\bar{P} + \bar{L}} + 2.80\right)\frac{25.4}{\bar{D}}\right] + 0.50$$

when values are expressed in mm.

Having developed these coefficients, it is possible to compute the amount of precipitation ($\hat{P}$) that should have occurred during a particular month to sustain the evapotranspiration, runoff and moisture storage that could be considered as "normal" and appropriate for the climate, having taken account of antecedent moisture conditions. The equation is

$$\hat{P} = \alpha\, PE + \beta\, PR + \gamma\, PRO - \delta PL,$$

where the potential values are those that apply to the particular time in question.

This computed precipitation is, in fact, an adjusted normal precipitation, the adjustment being dependent on the antecedent weather – as reflected by the computed moisture storage – and on the anomaly of the potential evapotranspiration during the month in question. Over the long term the mean of the computed precipitation is equal to the mean of the actual precipitation. But, for a particular month the actual precipitation minus the computed precipitation provides a measure *(d)* of the degree to which the month was abnormally wet or abnormally dry. When multiplied by the weighting factor, K, the moisture anomaly index, $Z = Kd$, provides a measure which is comparable in space and time.

Inasmuch as a succession of months, most of which were abnormally dry, produces a drought of gradually increasing severity, the final drought index (X) depends on the sequence of Z values. These were combined by the empirical equation

$$X_i = X_{i\text{-}1} + \frac{Z}{3.0} - 0.103X_{i\text{-}1}.$$

Table X shows a computational layout which has been developed in the practical application of this model.

This procedure is readily adaptable to electronic computers and it is usual to compute a number of check totals, etc. The computer output designed by Palmer contains the following items in the model:

STA = station number
YR = year
MO = month 01 = January 02 = February etc.
P = monthly precipitation (in.)
T = mean monthly temperature (°F)
SP = available moisture in the soil at the start of a month (maximum = 8.0 in.)
SS = amount of available moisture in the surface soil at the end of a month (maximum SS = 1.0 in.)
SU = amount of available moisture in the underlying soil at the end of a month (maximum SU = 7.0 in.)
PE = monthly potential evapotranspiration (Palmer uses the Thornthwaite method (Palmer, 1958)
PL = monthly potential water loss
PR = potential recharge; at the start of a month this is the number of inches required to bring the soil to field capacity (PR = 8.0 – SP)
R = monthly recharge; net gain in the surface and underlying soil
L = monthly moisture loss from the surface and underlying soil
ET = monthly evapotranspiration
RO = monthly runoff
ALPHA = coefficient of evaporation $\frac{\Sigma ET}{\Sigma PE}$ (for 30-year period 1931-1960)
BETA = coefficient of moisture recharge $\frac{\Sigma R}{\Sigma PR}$ (for 30-year period 1931-1960)
GAMMA = coefficient of runoff $\frac{\Sigma RO}{\Sigma S}$ (for 30-year period 1931-1960)
DELTA = coefficient of moisture depletion $\frac{\Sigma L}{\Sigma PL}$ (for 30-year period 1931-1960)
KAPPA = climatic characteristic (for 30-year period 1931-1960)
CET = estimated monthly evapotranspiration (= α.PE)

TABLE X

Palmer drought analysis
(Monthly data)

Year ____________

Location ______________________ Lat. ________ N. ________ Heat index ____________ Water storage cap. ________

		Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug.*	*Sept.*	*Oct.*	*Nov.*	*Dec.*
Precip. (in.)	P												
Temp. (F°)	T												
Pot. evapotr.	PE												
	$P\text{-}PE$												
Sfc. moist. chg.	S												
Sfc. moist.	S_s												
Subsoil moist. chg.	ΔS_u												
Subsoil moist.	S_u												
Initial moist.	S'												
Pot. recharge	PR												
Moist. recharge	R												
Moist. loss	L												
Evapotransp.	ET												
Runoff	RO												
Pot. moist. loss	PL												
$\overline{ET}/\overline{PE}$ =	α												
$\overline{R}/\overline{PR}$ =	β												
$\overline{RO}/\overline{S'}$ =	γ												
$\overline{L}/\overline{PL}$ =	δ												
αPE =	$\hat{ET}$												
βPR =	$\hat{R}$												
$\gamma . S'$	$\hat{RO}$												
$\delta . PL$	$\hat{L}$												
$ET + R + RO - L$ =	$\hat{P}$												
$P - \hat{P}$ =	d												
Weight factor	K												
Kd =	Z												
$Z + 0.15$ =	U_w												
$Z - 0.15$ =	U_d												
ΣU =	V												
$-2.69X_{3,i\text{-}1} \pm 1.50$ =	Z_e												
$Z_e + V_{i\text{-}1}$ =	Q												
V/Q =	P_e												
	$Z/3$												
Incipient – 0.103	$X_{1,i\text{-}1}$												
Wet	ΔX_1												
Spell	X_1												
Incipient – 0.103	$X_{2,i\text{-}1}$												
Dry	ΔX_2												
Spell	X_2												
Established – 0.103	$X_{3,i\text{-}1}$												
Wet or dry	ΔX_3												
Spell	X_3												
Final index	X												

Note: X_1 or X_2 or $X_3 = X_{i\text{-}1} + Z/3 - 0.103\ X_{i\text{-}1}$

CR = estimated monthly soil-moisture recharge (= β.PR)
CRO = estimated monthly runoff (= γ.SP)
CL = estimated monthly soil moisture loss (= δ.PL)
CP = estimated monthly precipitation (= CET + CR + CRO − CL)
CD = monthly departure for a particular month (= P − CP)
Z = moisture anomaly index for a particular month (= K.CD)
UD = amount of dryness effective in ending a wet spell (= $-Z - 0.15$)
UW = amount of wetness effective in ending a drought (= + Z + 0.15)
V = accumulated value of UD or UW
ZE = moisture anomaly required to end a "weather spell" in a single month (= $-2.691X_{i-1} \pm 1.50$)
(+ 1.50 when X_{i-1} is +ve, −1.50 when X_{i-1} is −ve)
PROB = percentage probability that a spell has ended (= $\dfrac{V_i}{ZE + V_{i-1}}$
X1 = severity index for a wet spell that is becoming established
X2 = severity index for a drought that is becoming established
X3 = severity index for any wet spell or any drought that has become definitely established
X = index of drought (or wet spell) severity; temporarily unassigned when $0 < \text{PROB} < 100$.

The equation for the drought index is

$$X_i = X_1 \text{ or } X_2 \text{ or } X_3 = X_{i-1} + \frac{Z_i}{3} - 0.103X_{i-1}$$

Table XI is a copy of a computer print-out showing values of the above items for North Platte, Nebraska (U.S.A.), for the months January to October 1952. Figure 6 shows plotted values of the index for a sample 20 years for North Platte.

Figure 7 shows the extent of drought severity by the Palmer index method over the United States for one (1934) of several years which were notorious for the extent and severity of drought in that country. The following table lists the combined areal extent of *extreme* and *very extreme* drought in each of the years and the predominant months when the maximum severities occurred.

1934	4.4 × 10^6 km^2	July and August
1936	2.1 × 10^6 km^2	August and September
1954	3.1 × 10^6 km^2	May and September
1956	2.3 × 10^6 km^2	September and October

4.2.5 *Baier-Robertson method*

This is typical of a number of methods which endeavour to make realistic assumptions regarding the extraction of soil moisture by plants and follows on from and modifies the earlier methods of Thornthwaite, Penman and Kohler. It has been demonstrated (e.g. Holmes and Robertson, 1959) that under non-irrigation conditions a water balance which takes account of soil-moisture stress and plant rooting characteristics is superior to simpler soil-moisture budgets which do not incorporate these features.

A method for the estimation of daily soil moisture on a zone-by-zone basis from standard climatological data was put forward by Baier and Robertson (1966). This method uses a climatological estimate of potential evapotranspiration (Baier and Robertson, 1965) as the upper limit of the actual transpiration and adjusts the latter according to available soil moisture, runoff and drainage. It also subdivides the total available soil moisture into

TABLE XI

Showing computer output of items in derivation of Palmer drought index for North Platte, Nebraska, U.S.A.

```
 STA    YR   MO      P      T     SP     SS     SU     PE     PL     PR      R      L     ET     RO   ALPHA    BETA   GAMMA   DELTA  KAPPA
24023 1952    1   0.74   27.8   5.73   1.00   5.47   0.00   0.00   2.27   0.74   0.00   0.00   0.00  1.0000  0.0732  0.0000  0.2255  2.308
                   CET     CR    CRO     CL     CP     CO      Z     UD     UW     ZE      V   PROB      X1      X2      X3       X
                  0.00   0.17   0.00   0.00   0.17   0.57   1.32   0.00   0.00   0.00   0.00    0.0    0.00    0.00    7.03    7.03

 STA    YR   MO      P      T     SP     SS     SU     PE     PL     PR      R      L     ET     RO   ALPHA    BETA   GAMMA   DELTA  KAPPA
24023 1952    2   0.80   31.5   6.47   1.00   6.27   0.00   0.00   1.53   0.80   0.00   0.00   0.00  1.0000  0.0928  0.0000  0.5170  2.126
                   CET     CR    CRD     CL     CP     CD      Z     UD     UW     ZE      V   PROB      X1      X2      X3       X
                  0.00   0.14   0.00   0.00   0.14   0.66   1.40   0.00   0.00   0.00   0.00    0.0    0.00    0.00    6.78    6.78

 STA    YR   MO      P      T     SP     SS     SU     PE     PL     PR      R      L     ET     RO   ALPHA    BETA   GAMMA   DELTA  KAPPA
24023 1952    3   0.98   30.8   7.27   1.00   7.00   0.00   0.00   0.73   0.73   0.00   0.00   0.25  1.0000  0.1361  0.0133  0.1582  1.784
                   CET     CR    CRO     CL     CP     CO      Z     UD     UW     ZE      V   PROB      X1      X2      X3       X
                  0.00   0.10   0.10   0.00   0.20   0.78   1.40   0.00   0.00   0.00   0.00    0.0    0.00    0.00    6.54    6.54

 STA    YR   MO      P      T     SP     SS     SU     PE     PL     PR      R      L     ET     RO   ALPHA    BETA   GAMMA   DELTA  KAPPA
24023 1952    4   1.20   47.4   8.00   0.74   7.00   1.46   1.40   0.00   0.00   0.20   1.46   0.00  0.9404  0.1752  0.0115  0.2381  1.456
                   CET     CR    CRU     CL     CP     CO      Z     UD     UW     ZE      V   PROB      X1      X2      X3       X
                  1.37   0.00   0.09   0.33   1.13   0.07   0.10  -0.05   0.00 -16.11  -0.05    0.3    0.03    0.00    5.90    5.90

 STA    YR   MO      P      T     SP     SS     SU     PE     PL     PR      R      L     ET     RO   ALPHA    BETA   GAMMA   DELTA  KAPPA
24023 1952    5   3.20   58.1   7.74   0.80   7.00   3.14   2.84   0.26   0.06   0.00   3.14   0.00  0.8421  0.1093  0.0466  0.2892  1.175
                   CET     CR    CRO     CL     CP     CD      Z     UD     UW     ZE      V   PROB      X1      X2      X3       X
                  2.64   0.03   0.36   0.82   2.21   0.99   1.16   1.01   0.00   0.00   0.00    0.0    0.00    0.00    5.68    5.68

 STA    YR   MO      P      T     SP     SS     SU     PE     PL     PR      R      L     ET     RO   ALPHA    BETA   GAMMA   DELTA  KAPPA
24023 1952    6   0.33   75.0   7.80   0.00   2.08   5.85   5.22   0.20   0.00   4.93   5.26   0.00  0.7747  0.0171  0.0587  0.3976  1.205
                   CET     CR    CRO     CL     CP     CD      Z     UD     UW     ZE      V   PROB      X1      X2      X3       X
                  4.53   0.00   0.46   2.07   2.92  -2.59  -3.12  -3.27   0.00 -13.79  -3.27   23.7    0.00   -1.04    4.06   -1.04

 STA    YR   MO      P      T     SP     SS     SU     PE     PL     PR      R      L     ET     RO   ALPHA    BETA   GAMMA   DELTA  KAPPA
24023 1952    7   1.53   74.8   2.08   0.00   1.31   5.90   2.12   5.12   0.00   1.57   3.10   0.00  0.6031  0.0053  0.0027  0.5551  1.173
                   CET     CR    CRO     CL     CP     CD      Z     UD     UW     ZE      V   PROB      X1      X2      X3       X
                  3.56   0.03   0.01   1.16   2.41  -0.88  -1.04  -1.19   0.00  -9.42  -4.45  -35.1    0.00   -1.28    3.30   -1.28

 STA    YR   MO      P      T     SP     SS     SU     PE     PL     PR      R      L     ET     RO   ALPHA    BETA   GAMMA   DELTA  KAPPA
24023 1952    8   4.03   73.9   1.31   0.00   1.09   5.35   0.87   6.60   0.00   0.22   4.25   0.00  0.5144  0.0147  0.0000  0.6008  1.430
                   CET     CR    CRO     CL     CP     CD      Z     UD     UW     ZE      V   PROB      X1      X2      X3       X
                  2.75      0.100.00   0.52   2.33   1.70   2.44   2.29   0.00  -7.37  -2.17   18.3    0.01   -0.33    3.77   -0.33

 STA    YR   MO      P      T     SP     SS     SU     PE     PL     PR      R      L     ET     RO   ALPHA    BETA   GAMMA   DELTA  KAPPA
24023 1952    9   0.67   64.9   1.09   0.00   0.71   3.49   0.48   6.91   0.00   0.38   1.05   0.00  0.4779  0.0354  0.0000  0.4355  1.405
                   CET     CR    CRO     CL     CP     CD      Z     UD     UW     ZE      V   PROB      X1      X2      X3       X
                  1.67   0.24   0.00   0.21   1.70  -1.03  -1.45  -1.60   0.00  -8.64  -3.77   34.9    0.24   -0.78    2.90   -0.70

 STA    YR   MO      P      T     SP     SS     SU     PE     PL     PR      R      L     ET     RO   ALPHA    BETA   GAMMA   DELTA  KAPPA
24023 1952   10   0.24   47.9   0.71   0.00   0.01   1.31   0.12   7.29   0.00   0.09   0.33   0.00  0.5292  0.0265  0.0000  0.7104  1.861
                   CET     CR    CRO     CL     CP     CD      Z     UD     UW     ZE      V   PROB      X1      X2      X3       X
                  0.69   0.19   0.00   0.08   0.80  -0.56  -1.05  -1.20   0.00  -6.29  -4.97   49.4    0.00   -1.05    2.25   -1.05
```

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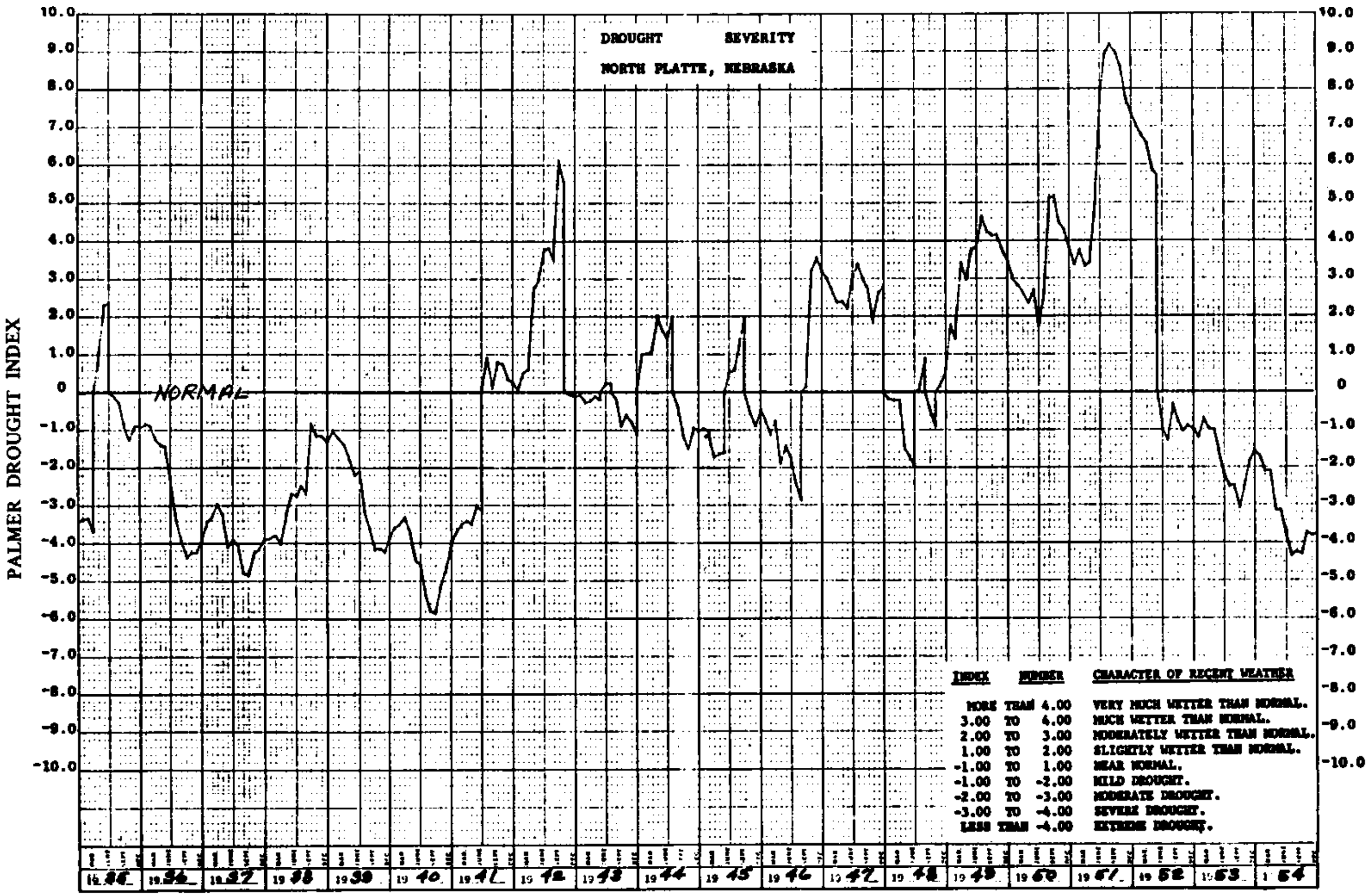

Figure 6 – Drought severity by Palmer index

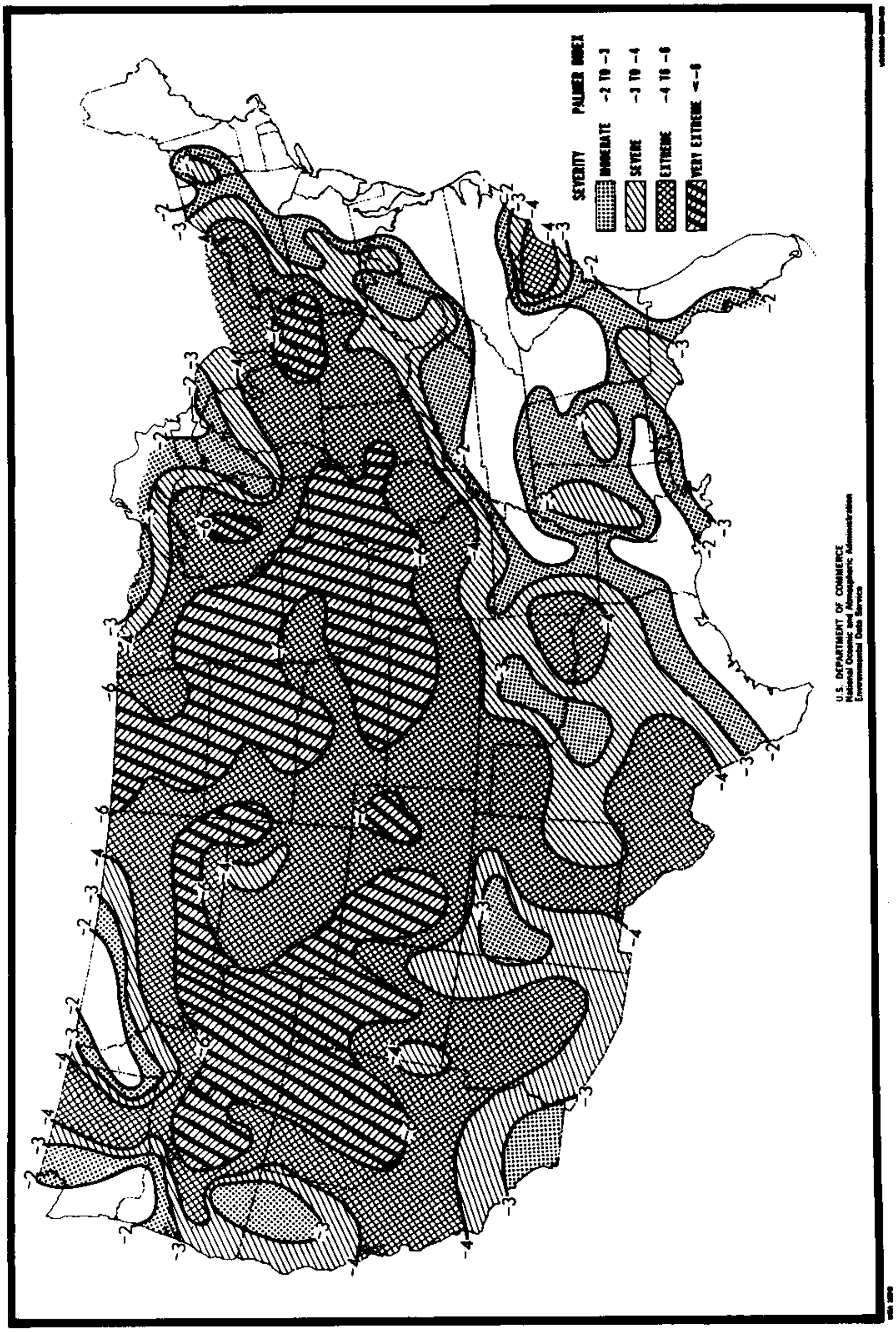

Figure 7 – Maximum drought severity over the U.S.A., 1 May to 31 October 1934

several zones of different capacities. It thus allows for the simultaneous withdrawal of moisture from different depths of the soil profile permeated by roots, in relation to the potential evapotranspiration, root concentration and available soil moisture in each zone. A feature of the model is the choice of different types of soil-drying curves, which makes it possible to test various concepts of the availability of soil moisture to plants in relation to soil and meteorological factors. Figure 8 shows various proposals relating evapotranspiration to available soil moisture. In their work, it was found that there was good agreement between observations from Colman electrical resistance blocks and estimates using type C and E soil-drying curves. Over the whole range of the soil-moisture cycle, statistical *t*-tests indicate that the use of type C relationship resulted in the best estimates, thus supporting the use of "linear" relationship originally proposed by Thornthwaite. However, when the available moisture content in the soil approaches zero, even small errors in the estimates become important and could be corrected by adjusting the crop coefficients or by using a more efficient relationship such as type E.

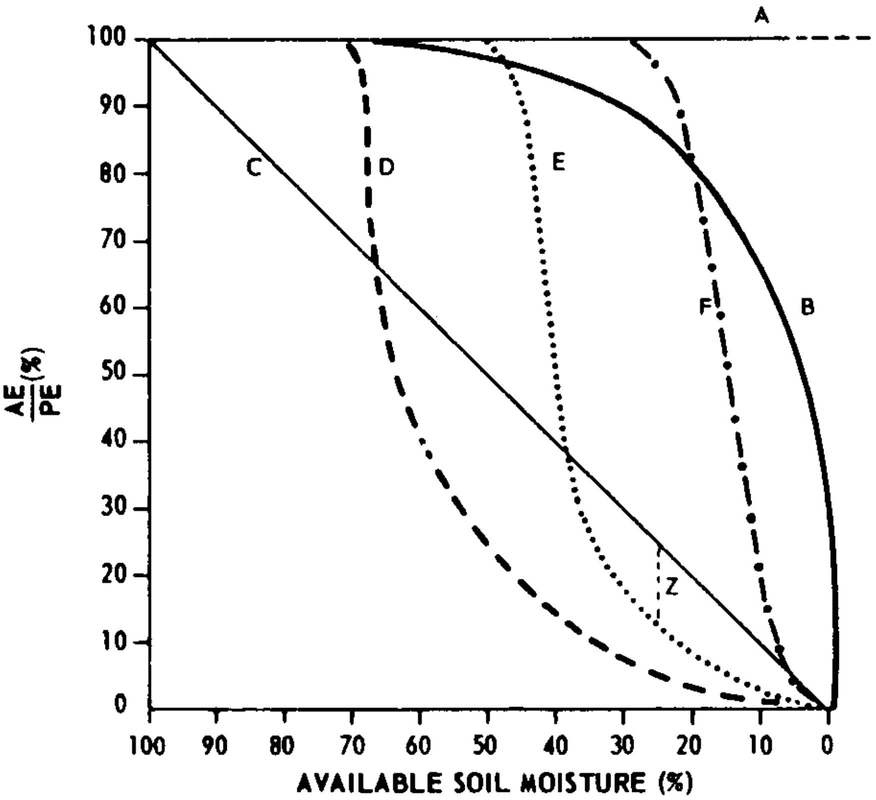

Figure 8 – Various proposals for the relationships between AE/PE rate and available soil moisture. *(After Baier and Robertson, 1966)*

Figure 9 show the estimated soil moisture available to plants, in each of six zones in the soil using type C moisture-extraction rate.

4.2.6 *U.S.S.R. methods*

U.S.S.R. workers have used water-balance methods in the prediction of crop yields, based on soil moisture, stage of crop development, soil type and evapotranspiration.

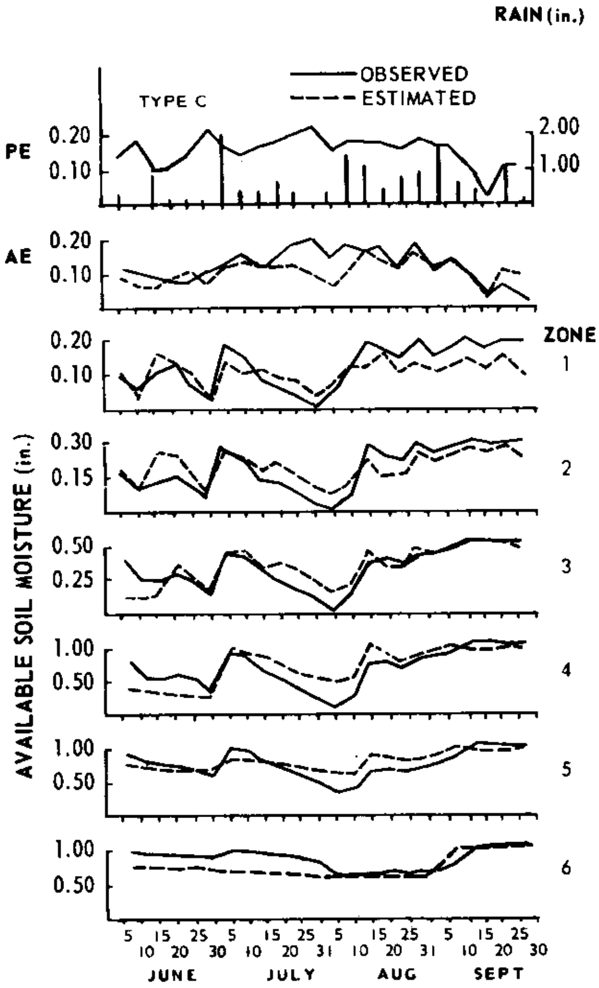

Figure 9 – Plant available soil moisture in six zones under short grass at Ottawa, observed and estimated from VB using type C relationship between available moisture and AE/PE rate: 1959. (One inch = 25.4 mm)

Direct soil-moisture measurements are a feature of the U.S.S.R. hydrometeorological networks and, for many water-balance studies, specific observations are available. These measurements can usually be extended to cover special requirements such as local studies not covered by the general network. Observations within the three most important local crops are maintained at each agrometeorological station and in addition on many of the State farms. Thus most U.S.S.R. investigators rely on direct measurements of soil moisture rather than on estimations.

However, methods of estimation have been developed for use where observations are not available or impracticable. For example, nomograms have been computed for the evaluation of variations in soil-moisture supply during each ten-day interval of the vegetation period as a function of meteorological, plant and soil parameters.

Fedoseev (1962) quotes the use of a "wetness" coefficient *K* representing the ratio of total moisture content in one metre of soil in a typical orographic element to that in a flat field. Thus corrections can be made for soil-moisture difference caused by variations in surface relief. Table XII shows typical values of the coefficient.

TABLE XII

Mean values of the "wetness" coefficient *K* in different types of orographic relief in the Kazakh S.S.R.

Relief type	*K*	*Relief type*	*K*
Hillock relief		*Variable relief in semi-deserts*	
Flat surface between hillocks	1.00	Micro-ridge	1.00
Top of hillock	0.46	Micro-slope	1.24
Southern slope	0.53	Micro-trough	1.58
North-western slope	0.71	Northern slope	1.12
Hollow relief		Trough of northern slope	1.27
Flat watershed	1.00	Bottom of hollow	1.40
Southern slope	0.76		
Trough on southern slope	1.07		
Foot of southern slope	0.94		
Lowland meadow	1.41		

Maximum soil-moisture differences caused by surface relief occur in moist years. *K* values tend to decrease during the normally dry seasons.

Fedoseev uses the following empirical equations to compute soil moisture:

(a) Soil moisture supply greater than 60 per cent of field capacity $U = -1.98x + 1.64y - 0.36Z + 32$

(b) Soil moisture between 60 per cent of field capacity and wilting point $U = -0.63x + 0.49y - 0.22Z + 8.2$

(c) Soil moisture below wilting point $U = -0.03x + 0.49y - 0.15Z + 1.4$

where

U = variation of available moisture (in mm) in 0-1 m layer during a ten-day period;
x = mean air temperature in a ten-day period (°C);
y = amount of precipitation in a ten-day period (mm);
Z = soil moisture at beginning of a ten-day period (mm).

U.S.S.R. workers have used the well-known water balance, energy balance and aerodynamic methods in a variety of forms to estimate evaporation. A number of empirical methods have also been developed and will not be elaborated here. However, the Budyko method for computing evaporation from small land surfaces is of particular interest as it uses precipitation as well as radiation. The equation developed by Budyko is:

$$E = \sqrt{\frac{B_0 P}{L}\left(1 - e^{\frac{B_0}{PL}}\right) \cdot \text{th}\,\frac{PL}{B_0}}$$

where P is the annual precipitation for a given point (in cm);

B_0 is the radiation balance for a moist surface (Kcal/cm^2 year);
L is latent heat of vaporization (Kcal/cm^3);
e is base of natural logarithms;
th is hyperbolic tangent.

The ratio B_0/L expresses evaporative potential, i.e. the maximum potential evaporation which would occur under the given meteorological conditions only if the land surface were sufficiently moist.

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CHAPTER 5

THE PLANT, AGRICULTURAL PRACTICES AND DROUGHT

5.1 Drought resistance

Drought-resistant plants are those varieties which are able to grow and yield satisfactorily in areas liable to periodic drought. May and Milthorpe (1962) separate three types of drought resistance:

(a) Drought escape – ability to complete the life cycle before being subjected to serious water stress;
(b) Drought endurance with *high* internal water content – capacity to survive drought by virtue of a deep root system or reduced transpiration;
(c) Drought endurance with *low* internal water content during the period of drought but ability to recover and grow rapidly when soil water is replenished.

The most important factor in drought resistance of crops in seasonally arid areas (e.g. wheat in Australia) is the ability to mature before the onset of (summer) drought. As the actual rate of transpiration will be less than the potential if the ground is not completely covered, crops in dry areas may be sown at wider spacing than in moist areas to permit the development of more extensive root systems. Root extension in depth is also important to provide access to a potentially large supply of water, and lateral extension within this zone is necessary to extract a high proportion of it. Sorghum is more drought-resistant than corn because of differences in root concentration. Root growth varies with many factors: species, age, density, radiation, transpiration, soil-water potential and other soil characteristics, frequency of defoliation. The establishment of a plant is aided by rapid root growth in the seedling stage and greater drought-resistance is shown by those plants with deeper and more extensively branched root systems. Root extension virtually ceases in most species during flowering and fruit growth so that plants with rapid rates of fruit growth have the greatest chance of achieving their full yield potential. The availability of water to plants depends to some extent on the soil type. On coarse sands most of the water is readily available and plants make rapid growth until transpiration depletes the supply; they then suffer a sudden and severe deficit and death may follow if the root zone is not then re-wetted. On heavy clay, however, water is held with progressively increasing tension as the content is reduced below field capacity. Plants then experience transient water deficits which reduce the rate of growth but water continues to be released as the tension progresses to the permanent wilting point. The reduced growth rate, the progressive drought hardening and the much greater amount of water available to the plant between periods of re-wetting allow growth to continue for longer periods on clays than on sands and adequate yields can often be obtained especially if the variety has a deep and extensively branched root system and a low cuticular conductance.

Transpiration will be less than the potential rate if stomata close for part or all of the day as a result of water stress in the plant, the actual difference being a function of the extent and duration of stomatal closure and the magnitude of the cuticular conductance for water vapour. A plant in which the latter is low and in which stomata close in response to small reductions in leaf turgidity in such a way as to allow stomatal opening for a part of the day, and so permit sufficient photosynthesis for growth without maximum loss of water, would have a considerable degree of drought-resistance. Plants with rigid cell walls would be expected to show greater drought-resistance than those with elastic cell walls as a small reduction in protoplasmic water would lead to the development of a lower water potential and hence greater flow into the cell with less disruption of metabolism.

Approximate relationships exist between relative turgidity (ratio of water present to that held at full turgidity), water potential of tissue and osmotic concentration of cell sap; the form of the relationship varies with the species. There is also a fairly close relationship between stomatal response and relative turgidity; measurement of stomatal changes may often provide the most convenient means of detecting water stress in the plant as well as indicating departures of transpiration from the potential rate. Respiration rate is also influenced by changes in turgidity; generally, as turgidity decreases respiration first increases; but as the water deficit becomes more severe or is prolonged, the rate decreases and ultimately falls below that of turgid tissue. Photosynthesis usually responds in the reverse direction as the deficit becomes severe. Plant growth is thus reduced by a decrease in relative turgidity, usually when the latter falls below about 90 per cent. The overall reduction in yield will therefore depend on the number, duration and intensity of periods of water stress experienced by the plant during the growing period.

Water stress influences the growth of organs in the following order of decreasing severity: leaves > stems > roots, i.e. there is an increase in the ratio of root to top growth under stress conditions while the ratio of lateral roots to total root length decreases. On restoration of full water supply the situation is reversed. There is little quantitative evidence available concerning the effect of different degrees of turgidity on the rates of the various physiological processes, nor on the minimum relative turgidity which can be experienced without death. Susceptible leaves on some forage shrubs and grasses may dry during a period of water deficit whilst resistant tissues in buds at stem bases survive. However, May and Milthorpe (1962) emphasize that drought-resistance in crops cannot be due to resistance of tissues to desiccation. After recovering from a period of drought, plants are usually much more resistant to the influences of further water stress.

Ripe seeds can survive extreme desiccation and this tolerance continues during the early stages of germination but decreases rapidly before emergence. Seeds which have been subjected to pre-sowing hardening treatment have been shown to yield ten to twenty per cent higher than untreated seeds under drought conditions (Genkel, 1946).

Seeds exhibit various germination characteristics which serve as a means of preserving the species through adverse conditions. Some seeds germinate either immediately upon ripening or after some delay ranging up to several years (Oppenheimer, 1960). Some plants produce more than one type of seed, each having different germination-regulating mechanisms. Typical is *Atriplex rosea*, whose black seeds germinate considerably later than its brown seeds; most will not germinate at all in the first season. Many annuals reduce the danger of extermination in dry conditions by profuse seed production; very dense growth of seedlings follows rainfall. However, serious competition leads to the elimination of the weakest, which are thus prevented from reproducing.

Natural selection and evolution have produced xerophytic plant types highly fit to survive under the hard conditions prevailing in semi-arid and arid areas. These plants can withstand not only drought but sometimes also intense heat and radiation as well as the impact of high winds and the aggravating effects of sand storms and siroccos. However, not all plants living in dry regions are necessarily adapted to drought as evidenced by the ephemeral annuals which germinate, develop and ripen seeds within a few weeks and thus escape the influence of very long recurrent periods of dry weather.

From the plant-breeding point of view, the particular climate which is required for the plant should be taken into consideration; e.g. in the Mediterranean type of climate the high yield of a winter crop should be combined with early maturity to avoid summer drought. The roots of a summer crop in an area of intermittent rain should have deep soil penetration and intensive branching which provides the greatest supply of water, while the leaves should have sensitive stomata and low cuticular conductance, thus conserving leaf turgidity under conditions of high potential transpiration.

Drought-hardiness is very akin to frost-hardiness and Levitt (1956) has drawn a number of comparisons. The main basis for the comparison appears to be that both frost and drought injury are mechanical in nature owing to the dehydration of the cell. Since drought injury occurs at very much higher temperatures, it is likely to be metabolic in nature, although it cannot be due to simple starvation. Young leaves are more drought-resistant than older ones, not only because of their higher osmotic values but also because of their higher protein content which is well above the minimum necessary for life.

5.2 Response of plants to drought conditions

Not all parts of a plant react to drought in the same way. According to Molga (1962) the upper leaves of the plant maintain their physiological activity the longest by drawing water from lower leaves. The latter are first to wilt or dry up during a drought. The upper leaves also draw water and certain easily mobilized nutrients from the floral primordial in which case the drought causes failure of the seed crop.

It is not unusual for plants under such conditions to develop short lateral shoots with tiny leaves from the axils of the dropped old leaves. These new small thickish leaves can be kept alive and turgid even with a much reduced water supply from the roots. If the drought occurs during the seed formation in grain the seed will be small, deprived of adequate amounts of nutrient substances, its size being inversely proportional to area of the assimilating surface of the plant. For this reason, the worst conditions for high grain yields occur when drought follows favourable meteorological conditions which produce an abundance of vegetation early in the vegetative period.

Drying out of the tilled layer of the soil at any time during the vegetative period has an adverse affect upon yields. However, with respect to grains, the greatest yield reduction takes place when drought occurs during or immediately after the stem elongation stage, i.e. at the beginning of the heading stage.

The increased sensitivity of grains to droughts during the period from rooting to heading stage is well known. In addition to the development of the main and coleoptile roots, the floral primordia also develop during this period. The development of spikelets coincides most frequently with the appearance of the fourth leaf. If the tilled layer dries out during this period the number of spikelets is greatly reduced. Particularly adverse in this respect is the combination of drought and high temperature. These conditions also reduce the number of heads which are formed at this time. This leads to the reduction of yield even though moisture conditions improve during later stages of development (Kulik, 1957).

Prolonged dry periods coupled with the absence of effective water in the one-metre soil layer reduce yields to zero. If there is some effective water in the 20-100 cm soil layer, dry periods reduce the yields but do not ruin them completely. Any additional water accumulated during the fallow period prior to seeding becomes highly significant under these conditions. Insufficient soil-water supply in spring frequently leads to undesirable consequences even though the amount of precipitation during summer months is normal.

5.3 Fallow as a management technique

The frequent cultivation of fields for the destruction of weeds is known as fallowing and it is claimed that the operation results in the conservation of water and the accumulation of nitrates (Staple, 1960). The efficiency of fallowing depends also on cropping systems, tillage methods, soil texture and frequency and distribution of rain. It is common practice in the seasonally cultivated wheatlands of the United States, Canada and Australia and has been proposed for the semi-arid zones of the Near-East (Perrin de Brichambaut and Wallén, 1963).

The prime purpose of fallow in the drier regions is to conserve water. Evaporation takes place from the bare soil surface at a reduced rate depending on soil water content, capillary conductivity, soil and air temperatures, relative humidity and wind speed. The maximum water that can be conserved for crop growth by the technique depends on the depth of root penetration and the water-holding capacity of the soil.

On the Canadian prairies, for example, where the practice of fallowing is frequently followed, land is allowed to lie idle for 21 months between the harvest of one crop and the planting of another. During this period about 20 to 25 per cent of the precipitation during the period is conserved as crop-available soil water. This conserved water is necessary along with the scanty growing season rainfall to produce an economical crop (Staple, 1960).

The need for fallow depends on the amount of water storage possible by alternative methods of cropping. In the southern plains of the United States the harvest is earlier and seeding later than in the north so that if seed-bed preparation is started early, the supply of water and nitrates for continuous cropping may be such that fallow is unprofitable. This situation is somewhat similar to that in the summer rainfall region of the Darling Downs, Queensland. There the winter wheat crop grows from June until November. Either a short fallow is maintained during the six-month interval December to May or a long fallow is continued through an additional 12 months until June of the following year. With short fallow the water gain to a depth of 120 cm varied from –8 to 125 mm with an average of 55 mm or 17 per cent of the rainfall. This additional storage was usually adequate to prevent crop failures.

Large areas of Russia have a continental climate where dry-farming with fallow must be practised to produce crops. The soil-water problem arising from scanty precipitation, with frequent fluctuations, both seasonal and annual, is most important in the grain-growing areas.

Factors influencing evaporation from fallow surfaces justify special mention and Staple (1960) has summarized work on this topic. Early workers showed that evaporation was related to the vapour concentration at the surface of the soil. Water was lost first at a constant rate, then at decreasing rates as the soil dried at the surface. Penman (1940) showed that on cool winter days soil surfaces were kept moist by capillarity and evaporation approached that from a free water surface, but in summer, when capillary movement was insufficient to meet evaporation loss, surfaces became dry and further evaporation was retarded. High summer evaporation rates from bare soil occurred only if the soil was frequently re-wetted.

Under winter rainfall régimes the soil usually dries out under summer crops and although soil temperatures are suitable for bacterial action, little nitrification takes place. Under these conditions fallow maintains soil water suitable for the accumulation of nitrates.

The need for clean fallow to destroy weeds in dry regions is sometimes underestimated. Drought and weeds have similar effects on crops and the drier the year, the more critical may be the water loss due to weeds. Staple (1960) also stresses that fallowing makes all soils more susceptible to wind and water erosion and he points out that wind and water erosion on sandy soils sometimes prohibit the use of fallow. In other locations fallow may be used safely only in longer rotations with sufficient grazing or hay crops to protect the soil and keep it in good physical condition. Water conservation may be enhanced by the practice of surface mulching which reduces evaporation, mostly during the short period after rain when the soil surface is moist.

5.4 Soil erosion

Primitive man rarely created problems in soil erosion even though he lived in a climate probably as variable as that of today. He was unable to change his environment to any significant extent and he lived within it in much the same way as any other animal. But man's ability to modify his environment has increased and today there are means for making drastic changes within an incredibly short space of time.

Now man changes ecosystems because the maximum sustainable biological productivity is either not enough or not what is wanted (Downes, 1968). In making these changes man has had considerable success but, in places, land has been destroyed and productivity has declined because he failed to understand that unless the new system of land use and management provided a dynamic stability, the system itself reacted to establish a new balance. It is this reaction which leads to erosion and in many parts of the world whole ecosystems have been destroyed and the productive capability reduced to a level from which it is exceedingly difficult to achieve satisfactory reclamation. Man makes wide-ranging changes to the ecosystem and in doing so changes the hydrology and exposes the soil to the effects of sun, wind and rain. However, periods of no rain may prove more destructive in the long term as drought under these conditions of changing land use may lead to serious soil erosion. Or, as sometimes happens in variable rainfall climate, drought and wind erosion are followed by heavy rain and serious water erosion.

The rate at which the stability of an ecosystem may be changed is usually governed by its climate. In climates favourable for plant growth there is usually a wide range of species and any alteration by man usually leads to only a change in species composition rather than complete destruction of vegetative cover. Drought would also be effective in much the same way. On the other hand, arid zone ecosystems have a specialized vegetation in which there is a limited number of species, all of which are affected by severe drought. In semi-arid or sub-humid climates with marked seasonal climatic variations, the hydrological balance of the system is vulnerable. By changing the vegetation from forest to grassland there can be significant changes in hydrology which alter the dynamics of the ecosystem to provide too little water in some parts of the season and too much in others. For example, runoff may be increased in the wet season so that the effects of drought are felt earlier as depleted soil-moisture storage is exhausted.

Contour ploughing, in which all lines follow the contours, or an alternative system, in which ploughing follows a predetermined "key-line", has been advocated in some areas for erosion control. Under conditions of moderate rainfall these plough-lines become water-ways where runoff is reduced to a minimum and infiltration is maximized. Sometimes mulching and other special surface tillage techniques are used in conjunction with contour ploughing. The technique is thus a special form of short-term fallow in which runoff is minimized and water is stored for later use by crops or pasture, thus helping to avoid drought.

5.5. Droughts and efficiency of applying fertilizers

Analysis of long-term data leads to the conclusion that in the same soil type in the main agricultural regions of the U.S.S.R. the efficiency of applying fertilizers decreases with decrease in precipitation and increase in potential evaporation. In each zone the efficiency is in the range ± 25 per cent. For winter grain crops it is given by the following equation:

$$E = \frac{\Sigma P}{150 + 0.45\Sigma d} - 50$$

where E is efficiency of applying fertilizer in per cent relative to optimum conditions;
ΣP annual precipitation in mm;
Σd sum of mean diurnal values of moisture deficit of air in mb.

According to this equation efficiency in non-irrigated areas under winter grain in the Crimea is 25 per cent relative to their efficiency in the northern regions of the forest-steppe zone. Comparison of the potential evaporation and precipitation gives only an approximation of the dependence of efficiency on the degree of aridity of an area.

To obtain a stable effect from fertilizer application it is necessary to take into account agrometeorological conditions as well as soil fertility. In 35 per cent of years in the Crimea aridity reaches the limit at which fertilizers do not produce a positive effect; the effect from nitrogenous fertilizers under these conditions can even be negative. Considerable success has been achieved in predicting the efficiency of fertilizer dressings.

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CHAPTER 6

PASTURES AND LIVESTOCK UNDER DROUGHT CONDITIONS

6.1 Introduction

6.1.1 *The problem*

In the semi-arid and sub-humid zones there is a scarcity of water for irrigation in a period of drought. However, even if water were available for this purpose, the cost of using it would not be justified in most of the areas involved. For these reasons, the only available strategy for complete or partial avoidance of the ravages of unexpected drought is good management of pastures and livestock. Since long-term forecasts of drought and rain are not yet possible this strategy must be founded on local and regional knowledge of the frequency and probability of drought and on a knowledge of the most effective methods of management of pastures and livestock under both normal and extreme weather conditions. Only a systematic and rational study of all the factors which make up the complete ecology of the different environments threatened by drought can help to achieve this objective.

Without attempting an exhaustive review of the very extensive works which might point to the solution of the problem, this chapter will try to indicate the different lines of investigation which might be followed in establishing the best methods of pasture and livestock management so as to avoid the ravages of drought.

6.1.2 *Pastures under drought*

The grazing lands were originally communities of natural vegetation made up of predominantly herbaceous species which wholly or partially covered the ground or shared the space with shrubs and trees in various proportions according to the climate and soil conditions. The extraordinary development of stock farming in the last two centuries caused a profound change in the animal life of these regions and in the vegetation subjected to intensive grazing. This led to the search for and study of techniques which would guarantee a stable level of production in the grazing lands, such as the introduction and cultivation of selected species of forage crops, cultivations and fertilizers to improve the natural and artificial prairies, and intelligent management of pastures and stock. Such research involved a preoccupation with methods of counteracting the effect on the vegetation of the drought which frequently affected the stock-farming areas. Those studies which form the basis of drought defence strategies for pasture lands fall into two main groups. First are those whose object was the study of the individual plant and its reaction to drought; and second are those which deal with the problem of the whole vegetative community in relation to drought.

6.2 Individual plants and drought

The study of the effect of drought on individual plants is important. The objective is the intelligent management of fodder species in the planning of livestock farming in regions subject to drought. Nothwithstanding the existence of extensive and sound reviews on the subject, for example by Crafts *et al.* (1949), Levitt (1951), Ruhland (1956), Wright and Streetman (1960), Gates (1964), Slatyer (1967) and Kozlowski (1968), it will be useful to mention specific contributions which indicate the lines of investigation and their results. In this way it will be possible to deduce how far the practical methods of pasture management are based on a knowledge of the relationship between the plant, as an individual, and the degree of drought. These investigations have established the nature of the plants' resistance and endurance to drought and revealed structural and mechanical properties and physiological processes underlying them. In addition, they have contributed to the development of a complete method of evaluating the degree of resistance and tolerance of plants to drought.

6.2.1 *Definitions of resistance and tolerance to drought*

Even though there is no unanimity in defining the nature of plant resistance to drought, various authors have tried to do so on the basis of existing research. The way many plant species grow in arid and semi-arid climates was one of the first observations used in classifying and explaining plant resistance to drought. Shantz (1927) distinguished various types of growth which enabled plants to exist in conditions of occasional or permanent water deficiency and typical among them were those in which growth is independent of the cycle of available moisture. He considered these to be an indirect adaptation to the environment rather than an internal defence mechanism against adverse conditions. He classified three categories: "drought-escaping plants" (those species, usually annuals, which, by rapid growth, can reach the reproduction stage before return of the drought); "drought-evading plants" (such as many perennial grasses which reduce their growth or stop growing during drought or, by a reduction of water use, delay the drying out of the soil and so prevent premature dehydration of their tissues); and lastly, "drought-enduring plants" (principally ligneous perennials like the desert shrubs which show very little seasonal growth even when water is occasionally abundant, and become dormant before water is scarce). The "drought-resisting plants", on the other hand, are defined by Shantz as those which can grow by virtue of the water in their tissues, such as the succulents and cacti. In the latter case, he considered that growth is independent of the dryness of the soil, although he recognized that even such species do not have the ability to extract water from the soil beyond the wilting point. Some authors before Shantz (1927), and several after him, have attempted to define resistance and tolerance by concepts based on the physiological processes in the tissues and sometimes even used these methods to evaluate them.

Synthesizing these criteria, Levitt (1956) defined what he called "drought-hardiness" as the difference in relative humidity which caused death by drought and that which, in equilibrium with the sap, maintained turgidity. This definition refers directly to the physiological processes resulting from drought injury and, indirectly, to methods of evaluation. Nevertheless, in considering the effects of drought on pasture plants, it will be useful to take into account the physiological aspect of injury, as well as other factors of similar effect such as the competing morphological and histological characteristics and growth behaviour as pointed out by Shantz (1927). The experiments of Went (1948, 1949) and of Went and Westergaard (1949) on the effect of temperature and rainfall intensity on germination of desert plants show the degree of adaptation of these species to the extreme conditions of their environment. Slatyer (1967) and Fitzpatrick *et al.* (1967) have likewise shown how the growth of some species of the Australian desert depends on the soil-moisture régime. The knowledge and use of these ideas may be very helpful in selection and improvement of pastures.

6.2.2 *The nature of drought injury*

Although understanding of the physiological processes of drought injury to plants is not yet complete and is partly based on incompletely established hypotheses, it is possible to divide the attempts to clarify them into two basic groups. The first includes those contributions which explain it as due to metabolic changes and by such important functions as photosynthesis, respiration, transpiration, osmosis and enzymatic processes such as the breakdown of proteins. In the other group are those which show mechanical damage to the cell structure due to alternate moistening and drying as well as to changes in elasticity and viscosity of the protoplasm. Although it is difficult to separate these two types of effect, many authors of differing schools of thought in western Europe (Stocker, 1947), Russia (Iljin, 1931; Henkel, 1946 and 1961; and Kursanov, 1956) and North America (Levitt, 1951 and 1956) assign more importance to this last aspect of drought injury.

6.2.3 *Structural and mechanical features of plants in relation to drought resistance*

Apart from the complex internal processes which determine drought injury in plants there are a number of structural and morphological features which, according to the form they take in particular species and cultivars, determine the degree of injury and, for that reason, define their tolerance or resistance to drought.

From the beginning of these studies of plant physiology, many researchers noted that the morphological, organographic and histological characteristics of plants bore a close relationship to their water requirements. This conclusion came primarily from the observation of species native of and adapted to arid and semi-arid regions, in which such properties ensured at least some retention of the water contained in their tissues. The leaves, which are the main organs of transpiration, have received most attention. Maximov (1929*(a)*, 1929*(b)*, 1931), summarizes such characteristics, known as xerophytism, as follows:

(a) Smallness of cells;
(b) Great thickness of the cell wall;
(c) Mesophyll protected by a thick cuticle;
(d) Large number of veins;
(e) Large number of stomata per unit area of surface.

Other authors, such as Löv (1926), Newton and Martin (1930) and Runyon (1934), also include such factors as:

(f) Bullate cells;
(g) Intercellular spaces;
(h) Incision of the leaves (deciduous foliage);
(i) Hairiness;
(j) Root-leaf ratio;
(k) Reduction in leaf size.

In spite of the agreement of the authors mentioned and the logic of the argument on the protective function – the retention of water in the plants – of the properties described, some authors have presented conflicting evidence and hypotheses. This shows the complexity of the phenomenon and suggests at least that, in their response to drought, both the morphological and the mechanical properties of plants have to be considered. Walter (1949) showed that many xeromorphic characteristics could be induced in plants grown in conditions of abundant light which increased the evapotranspiration from leaf surfaces, that is to say, a greater concentration of stomata per unit surface, smaller stomata, smaller cells in the epidermis and mesophyll, greater hairiness, greater thickness of the outer wall of the epidermis and cuticle. Ashby (1932) questioned, in some cases at least, whether defoliation might be a protective mechanism against drought; Grieve (1955) mentioned that some researchers were unable to agree on the usefulness of the effect of the bullate cells in rolling up the leaves during drought, perhaps because the effect occurred after irreversible injury to the plants. In the same way, some authors (Sayne, 1920) have observed that plant hairs sometimes increase transpiration while at other times they encourage condensation and epidermal absorption of water.

The closing of the stomata as a defence against excessive water loss has to be considered, taking into account that at the same time it may reduce photosynthesis and dry matter. As was shown by Loftfield (1921), Stalfelt (1929) and Larcher (1965) this can, in the long run, lead to a lack of adaptation to drought by the plant.

Extensive root development as a feature giving resistance to drought should be dealt with, as Cook (1943) advised, in conjunction with other characteristics – especially the transpiration surface. For instance, sorghum, which resists water shortage better than maize, has approximately twice the root volume and half the leaf area (Miller, 1916). The extensive root development of some arid-region shrubs, such as jarillas *(Larrea divaricata)* in Argentina, acacia in Palestine, and *Andira spp.* in Brazil, with roots of 10 to 19 metres, is associated with very little leaf surface and at the same time greater adaptation to arid climates (Morello, 1951, 1955-56; Oppenheimer, 1960; and Rawitscher *et al.*, 1943).

6.2.4 *Physio-chemical factors in plant drought resistance*

In spite of the fact that the structural and mechanical properties of plants are easy to observe, some authors in the first decades of this century assigned great importance to the internal physio-chemical processes of plants for ascertaining the phenomenon of drought resistance.

The idea of the resistance of vegetable tissues to desiccation without definite injury or with reversible changes was expounded by workers such as Stocker (1928), Maximov (1929*(a)* and *(b)*) and Iljin (1931) who related them to physio-chemical changes in the cells. Later investigations have given some evidence in favour of this hypothesis and shown the direction for further work.

Thus, mechanical injury to the cell structure, especially rupture of the cell membrane and of the protoplast as a consequence of intense plasmolysis preventing remoistening of the protoplasmic vacuoles, has been regarded as a fundamental effect of drought by writers such as Iljin (1931, 1952), and the theory of mechanical damage in the interior of the tissues has been based on it. This hypothesis is supported by the observation that tissues formed of cells with few vacuoles in relation to protoplasm are more resistant to desiccation. Nevertheless, writers such as Stocker (1947), Levitt (1951) and Henkel (1961) maintain that other processes with similar effects must be considered, e.g. change of viscosity of the ectoplasm, breakdown of proteins, etc., and that their role may be most important in drought injury.

Previously, other writers found a correlation between bound water and drought-resistance. Thus, Newton and Martin (1930) showed the following order of drought-resistance for three different grass species: *Agropyron tenerum, Agropyron smithii* and *Phleum pratense*, grown in similar conditions, containing respectively 10.3, 7.7 and 4.5 per cent bound water in their dry tissue. Culvert (1935), working with sap from wheat leaves, produced similar results, and Grandfield (1943) established that bound water in lucerne roots varied inversely with soil moisture.

The advances of recent years, aided by the use of the electron microscope, molecular chemistry and radioactive tracers, have brought confirmation of some of these hypotheses. Recent work (Webb, 1965) has shown that synthesis of proteins is closely associated with the activity of the nuclei acids RNA and DNA linked to them, and that cellular desiccation can lead to the destruction of these structures by the loss of bound water.

Other factors associated with important physiological processes such as water absorption, photosynthesis, transpiration and respiration have been shown to be related to drought-resistance. The work of Beck (1929) and Bartel (1947) showed a relationship between drought-resistance and the osmotic pressure of the tissues, confirming observations already made by Maximov (1929*(a)*, *(b)*) and Iljin (1957), who noticed this as a very marked characteristic of xerophytic species.

Although some authors interpret the effect of drought on functions such as photosynthesis, transpiration and respiration by the important influence it has on the stomata functioning, others have shown the direct consequences of the phenomenon on the biochemical processes which result from such important physiological functions.

Stocker (1956), on the basis of his own and others' work, concluded that photosynthetic processes decreased as the soil water decreased but that, if this decrease continued for some time, there was an increase of photosynthetic activity relative to the synthesizing surface and not to the total dry matter. He thus distinguished two phases or periods when plants are subjected to water stress, the first of reaction and the second of recuperation. The latter is characterized by an increase in respiration and a decrease in photosynthesis, both of which return to normal levels at the end of the drought stress if there is no definite injury to the structure. Intervening directly in this process are other mechanisms of the cellular metabolism, such as the balance of the normal levels of exudation and absorption of invertase and phenomena of proteolysis. If the drought stress continues, there may be a short period of regeneration before the death of the cell with a beginning of synthesis and recovery of starch.

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Contradictory results found by some workers in the search for a relationship between drought-resistance and physiological processes or in the mechanism of injury previously mentioned, show the need for a major study in this direction, for a standardization of methods used and for an adequate critical review of the results obtained. Thus, the work of Whitman (1941) and Carroll (1943) upholds the theory that bound water has no simple relationship with drought-resistance in the grasses studied by them. The latter author also attributes some importance to the sugar accumulation in grasses as an indicator of their specific resistance to drought. Kaloyereas (1958) found no relationship between resistance and the intensity of respiration and protein, pentosans, calcium and potash content in pine needles. As to the effect of water stress on photosynthesis and respiration, Brix (1962), working with pine seedlings, found that photosynthesis measured by CO_2 absorption decreased when the soil-moisture tension was 4 atmospheres and stopped when it reached 11 atmospheres, while respiration decreased between 8 and 16 atmospheres, increased between 16 and 32 atmospheres and again decreased steadily as tension increased to 48 atmospheres. In tomatoes, on the other hand, photosynthesis showed a decrease at 7 atmospheres and stopped at 14 atmospheres but the decrease in respiration was constant throughout.

6.2.5 *Evaluation of plant drought-resistance*

Various methods have been used to study the effect of drought on plants and to evaluate their specific resistance to drought. For analytical reasons, it is convenient to consider these from two basic aspects; the method of producing the effects of drought, and the means of appraising its effect on the plant.

The oldest and most used method of evaluating drought effect in plants is the open field experiment under natural drought conditions. This method, although offering the advantage of low installation costs, has serious disadvantages, such as the impossibility of separating the factors determining the extent of the drought from interference of outside effects, etc. For these reasons, to obtain satisfactory results by these methods a great many experiments are required which are not always successful.

The difficulties of field methods have given rise to the increasing trend towards experiments in which the drought is controlled independently of external conditions. These methods, while allowing easy isolation of the different factors determining the drought and those which have an indirect effect, also have their limitations. Among these are those which arise from the kind of plant, the number of specimens, development stages, time of exposure to drought, level of nutrition of the plants, their hardiness at the time of treatment, and the conditions of the controlled environment and of the soil in which the experiments take place.

In the study of the drought-resistance of forage species the disadvantages of the artificial drought methods are small. The herbaceous character of most of these species, their annual cycle or, at least, the completion of growth stages within the year, makes them specially suitable to this kind of method. In particular, work on seedlings or recently germinated seeds has established that, in perennial grasses, the seedling stage (Mueller and Weaver, 1942) and the first year of growth (Schulz and Hayes, 1938) are the most drought-sensitive periods. Work by Rogler (1954) on crested wheat grass *(Agropyron desertorum)* and by Kneebone and Cremer (1955) on native grasses of the U.S.A. indicated that the relative size of the seed, always indicative of vigour in the seedling, may be a useful feature in indicating the seedling's drought-tolerance.

Investigational methods in drought tolerance in which the phenomenon is produced and controlled artificially may, in turn, be divided into two main groups according to whether the drought is atmospheric or edaphic.

6.2.6 *Atmospheric drought*

Atmospheric drought, as the name suggests, is a condition brought on by a combination of factors existing simultaneously but with varying degrees of intensity in the atmosphere. Such factors include high atmospheric water-vapour pressure deficit usually accompanying high air temperatures, strong winds and intense sunlight. These factors in the right combinations may cause severe desiccation of plants even in the presence of apparently adequate soil moisture. The desiccation and resulting injury may be intensified by a cold soil, a limited root system and low soil moisture. Atmospheric drought must be distinguished from heat-stress or high-temperature injury. Although both conditions often occur simultaneously, high temperature may cause direct injury to cell protoplasm and to chloroplast and may upset several biochemical processes within plant tissue.

Atmospheric drought has been simulated by various methods, ranging from the simple and old-established method of warming the air in enclosed cabinets to climatic chambers in which light, temperature, humidity and ventilation are controlled. Controlled chambers, in which the soil was at different levels of high temperature but with adequate moisture, have been used to show the resistance of grass and weed seedlings to high temperatures and have explained the pattern of emergence which their species exhibit in the field (Laude, 1957).

The drought-resistance of mature forage plants has also been studied by means of various kinds of growth cabinets in which mainly air temperature and humidity are controlled. In some cases, after successive cuts and progressive rises in temperature (21.1, 26.7 and 29.4°C), the ability of the various species to resist the effects of the high temperatures was measured (Atwood and McDonald, 1946). In others, the periods of atmospheric drought were shorter, with the object of measuring injury and the suitability of different species of forage plants hardened to drought by various treatments. Carroll (1943) showed hardening of plants after subjection to a period of atmospheric drought and soil wetness.

Henkel (1961) in the U.S.S.R. showed how to harden various cultivated plants, especially cereals, on a large scale. He subjected seeds about to germinate to short periods of high temperature (30 to 35°C) and low humidity. In Argentina, it was possible to duplicate these experiments and confirm the increase in drought resistance of treated seeds (Michajlikov and Juarez, 1953; Michajlikov *et al.*, 1954).

As an example of more highly developed equipment for the study of atmospheric drought-resistance of forage crops and herbaceous plants in general, one may mention the design of Aamodt (1935), perfected by Kenway and Peto (1939), and the growth chamber of Shirley (1934). These used a combination of low humidity, high temperatures and light to moderate winds. In the last model a rotating table helped to equalize conditions of circulation, turbulence and exposure. With the first model, Aamodt and Johnson (1936) were able to measure the degree of drought tolerance of varieties of grass, clover and lucerne.

The very complex apparatus of environmental control, commonly called the "phytotron", which is used extensively in studies of plant physiology, can be used very effectively in studies of plant drought-resistance (Went, 1957; Johnson, 1959).

6.2.7 *Edaphic drought*

Numerous workers have attempted to investigate the behaviour of forage species under artificially produced edaphic drought. Generally, in these cases, the drought is induced in pots placed in trays which, suitably moist at the beginning, remain unwatered and are placed in a greenhouse. The plants are left either until they die or for a fixed period of time. At times renewal of watering may confirm the survival of individuals. The period of survival or the percentage surviving a predetermined period of drought can be transformed into an objective drought-resistance index. Platt and Darrouch (1942) and McAlister (1944) examined pure and hybrid populations of different species and confirmed results from field experiments and observations. For these reasons we may consider these methods adequate for the selection of drought-resistant clones and individuals.

Interesting experiments by Went (1948 and 1949) and Went and Westergaard (1949), using this method, explained the adaptation of Californian desert species, the relationship between their seed germination and temperature and rainfall intensity, and made possible a rational ecological classification of the species according to these relationships. Using a similar method, Olmsted (1942) was able to study morphological and histological changes brought about by droughts of from 46 to 48 days' duration in such major economic species as sideoats grama *(Boutelova curtipendula)*, which is abundant in the range land of the western United States. Small pots immersed in warm water were used by Julander (1945) to show that plants of buffalo grass *(Buchloe dactyloides)* and bermuda grass *(Cynodon dactylon)*, previously lightly watered and then immersed in water at 48°C for variable periods of time, showed an increased resistance to drying in such conditions over plants grown in soils with adequate moisture. Controlled chambers, in which the soil was maintained at various levels of high temperature but with adequate moisture, were used to establish the relative tolerance of six species of perennial grasses to high soil temperatures and, thus, the selection of species according to their seedling tolerance of excess warming in the soil (Shum and Biehler, 1952; Laude, 1957).

6.2.8 *Water deficit evaluation in plants*

The application of methods of evaluating plant drought-resistance, such as those mentioned, often requires the determination of indices of their physiological relationships. These indices are concerned with quantifying the water deficiency in the plant tissue in two basic and distinct ways – by a measure of the total water in the tissue or by means of their energy state.

The energy state, after the notation of Slatyer and Taylor (1961) and the formula of Barrs (1968), is given by the equation:

$$-\psi = -\pi - \psi_m (\pm) P$$

where ψ = total potential of internal water in the plant referred to that of pure free water;
π = osmotic potential;
ψ_m = matric potential which arises from the absorption forces of the colloids and the capillarity of the cell wall;
P = turgor pressure resulting from π and from the force of tension in the cell wall.

The total water content of plants at a given moment, according to several writers, may show the degree of water deficiency in the tissue, and by comparative studies between species and cultivars forms an adequate index for selection for drought resistance. It is necessary to refer this content to a fixed base for valid comparison. In the many investigations carried out, the standard of comparison has been the weight of dry matter, and of moist tissue, the leaf area and the water content at full turgor.

In fodder grasses the total water content at wilting point compared with the dry-matter weight has been measured by Paltridge and Mair (1936), who found that mesophyllic species wilted when they lost 50 per cent of their water while xerophytic species could lose 75 per cent. Bailey (1940) measured this limit as 41.6, 50.3 and 49.4 per cent respectively for *Agropyron smithii Rydb.*, *Agropyron ciliare (Trin.) Franch* and *Bromus marginatus Nees.*

Other work carried out on related species such as cereals may be mentioned here as examples of the application of these methods, but the general impression given by all of them is of temporal variations in the reference value. The moist and dry weights especially showed a diurnal variation and a more marked variation in cycles of several days made results obtained incompatible in their absolute values. The leaf surface also showed variations over single days and periods of several days, although between narrower limits (Thoday, 1909; Miller, 1917; Weatherley, 1950; Gej, 1962).

More logical and acceptable are those indices derived from total water content at a given moment compared with the water content at full turgor. In some models the total water content is compared with the total water potential. Related to this concept are the findings of Stocker (1928 and 1929*(a)*, *(b)*) in cutting leaves from plants, weighing them, then placing them in water in a closed space for 48 hours to reach full turgor. In this form the value of the actual water deficit in the tissues (weight at full turgor — fresh weight) and the total water content (weight at full turgor — dry weight), gives a water saturation deficit *(WSD)* more correctly referred to as the saturation deficit of tissue water:

$$WSD = \frac{\text{actual water deficit}}{\text{maximum possible content}} \times 100$$

Weatherley (1950, 1951) used leaf discs of constant area which after weighing he floated in water for 24 hours under diffuse light to regain full turgor, and proposed the index of relative turgor *(RT)* as the ratio of actual water content (fresh — dry weight) to the saturation content (weight at total saturation — dry weight).

$$RT = \frac{\text{actual water content}}{\text{maximum possible content}} \times 100$$

The same technique has been used on species where it is not possible to obtain leaf discs, such as those with glossy and ridged leaves, by adapting the method (Slatyer, 1960; Rychnowska and Bartos, 1962; Kozlowski and Clausen, 1965). Other expressions for the actual water deficit such as those referring to dry weight or weight of saturated tissue are less acceptable for this purpose than those already quoted.

Although there is an extensive bibliography on the application of these ideas to the measurement of deficit in specific fodder and related species, particular mention can be made of contributions by Oppenheimer (1954) on grasses; Namken and Lemon (1960) on maize; Fischer and Kohn (1966) on wheat; Begg *et al.* (1964) on bulrush millet and legumes; Jarvis and Jarvis (1963*(a)*, *(b)*) on lupins; Ehrler (1963) on lucerne; Shepherd (1964) on clover; and Slatyer (1960 and 1961) on *Acacia aneura*.

Indirect methods of estimating total water content of the tissues such as electrical and radioactive absorption methods have been developed in the last few years but they need constant direct operation for control and adjustment. The isolated measurement of the total potential energy of the water ψ, or of its components, osmotic potential π, the matric potential ψ_m and the turgor pressure P, have been developed in many laboratory studies using a wide variety of equipment, instruments and techniques directed more to the description of physiological processes of water deficiency than to its consequences on yield and productivity. Barrs (1968) has made an extensive critical review of these methods and their results.

6.3 **Plant communities and drought**

Although the study of the effects of drought on individual plants is important, it is also essential to be aware of its consequences on plant communities as a whole. Only a quantitative inventory of changes in the natural or artificial grasslands during the development of droughts, and an analysis of those factors which directly or indirectly affect these changes, can provide the basis of intelligent management of the grasslands in each region affected by a particular régime of drought.

Knowledge of the development of plant communities in arid and semi-arid regions which, in addition to the stresses of the natural environment also endure those imposed by livestock farming, has a greater practical importance than in humid regions. When moisture is a limiting factor local variation in topography, soil and other factors has more effect on plant communities than when moisture is not limiting. This induces a separation of populations according to genus and species and produces a more rapid phylogenetic evolution (Dobzhansky, 1950; Stebbins, 1952). At the same time, however, the destruction or imbalance of the ecosystems in arid and semi-arid areas is more difficult to repair.

6.3.1 *Study methods of dynamics of plant communities in pastures*

Many methods are used in the study of the evolution of plant communities in pastures. They are dependent on the particular changes being studied, on the local characteristics of the environment in which they will be used, and on the technical resources of the time. These methods classify changes in the community according to variations in the distribution of species and number of individuals, the area covered, height and weight. There are many detailed accounts of these methods, such as those of Brown (1954), Cain and Castro (1959), the National Academy of Science (1962) and others. Only a few will be mentioned here; in particular, those related to studies already discussed. One of the oldest and most costly methods has been the continual observation of particular species in small plots (between 1 and 30 square metres) which have been replicated over the area under study in order to determine the variation in the distribution of the species. This technique was used particularly in the twenties and thirties in the semi-arid region of the United States. Important conclusions were made regarding the management of the natural grasslands of that region frequently affected by drought and trampling by cattle (Nelson, 1934; Savage and Jacobson, 1935; Savage, 1937; Thomas and Young, 1954).

The "inclined-point-contact" method consisted of a framework inclined at 45° to the soil and having ten iron spikes (at intervals from a few centimetres up to 30 cm) making contact with the plant canopy, allowing measurement of plant height and density. The "belt transect method" consisted of the removal and mapping of principal herbaceous species, using a "standard" 30 cm^2 quadrant and chain, from a plot of 0.30 m X 6 m marked out by stakes. The "circular plot method" established plots of some 6 m radius, which were centred on the fixed stakes marking other transects, in which base diameter, height and vegetation layer covered by trees and shrubs were measured. Use of these methods reported by Thomas and Young (1954) established important conclusions on the dynamics of communities of forage plants and the factors governing them.

The comparison of vegetation subjected to grazing with areas deliberately enclosed enabled the separate effects of grazing and drought to be determined as well as the action and time required to restore the plant communities (Osborn, 1950; Thomas and Young, 1954; De Gásperi, 1959; Soriano, 1959).

Lastly, aerial photography and the use of remote sensors placed at the disposal of the modern worker a technique which enabled him to monitor, over large, medium and small areas, those changes due to man's activities and to natural phenomena such as drought (Poulton, 1970; Carneggio, 1970). Notable among the measurements possible using these methods were water content and erosion of the soil surface, identification of herbaceous species and shrubs, their evolutionary or phenological state (Reppert and Driscoll, 1970), and in some cases, even changes in physiological structure and alteration of functions in plants subjected to drought stress (Weber and Olson, 1967).

6.3.2 *Plant communities and drought injury*

Injury caused to plant communities by drought is the result of an interplay of factors which must be established so as to optimize the defensive strategy appropriate to each farming region. Among these factors are the botanical make-up of the community, soil type, stocking rate and normal grazing use, the type of farming, utilization of fodder, the competition of weeds and shrubs in the plant community and the types of animals and wild predators.

There are many references which indicate that severe drought brings about a real change in the natural vegetation. In these conditions those species most sensitive to drought tend to die out. Those annuals which do not reach the reproductive stage are most likely to suffer, but even perennials (grasses especially) which in slight drought survive at the expense of their sub-surface organs may die off completely during extreme drought. Savage and Jacobson (1935) and Savage (1937) observed in the semi-arid south and central Great Plains of the United States that drought, with a frequency of approximately once in 20 years, reduced the vegetation cover – mainly grasses – by 75 to 90 per cent in ungrazed pastures.

Thomas and Young (1954) observed the balance of populations of the three most important grass species growing in the more arid areas such as the western Edwards Plateau in Texas: tobosa grass *(Hilaria mutica)*, buffalo grass *(Buchloe dactyloides)* and curly mesquite grass *(Hilaria belangeri).* They found that even though the tobosa grass, the best of the three, dominated the other two, in dry years its density decreased significantly. The other two species suffered the effects of the drought to a greater degree. Although it is difficult to separate the influences of grazing and drought, close observation during drought confirms the resistance of tobosa grass, which is reduced in height and leaf density, and the greater mortality of buffalo and curly mesquite grass. Other species of poorer quality such as sideoats grama *(Bouteloua curtipendula)*, vine mesquite *(Pancium obtusum)* and purple three awn *(Aristida spp.)* suffer slight, moderate and severe drought respectively.

In arid climates, and particularly during drought conditions, researchers refer to the incursion of shrubs and thorny plants, which then compete for space with the more valuable forage species. Osborn (1950) reports that after a drought in south-west Texas lasting from 1946 to 1948, which had a probability of occurrence estimated at once in 50 years, there was an invasion of dry savannah shrubs such as *Prosopis juliflora.* Thomas and Young (1954) noted the shrub invasion after the lesser drought of 1953, and Carter (1964), for the same region, observed the increase in area occupied by the mesquite *(Prosopis glandulosa)*, after the drought of 1950-1956, which included that of 1953 mentioned above. Carter (1964) confirmed, moreover, that droughts of longer than two years can cause the death of mature mesquite, especially those in competition with other species growing on soils which induce a higher water potential, such as clays. In shrub associations such as *Acacia, Condalis, Opuntia, Aloysia, Celtis* and *Rhamus,* the same phenomenon is noticed, or at least the death of the aerial parts of these shrubs down to the crown of the buds.

In the arid and semi-arid climates of central Australia similar effects have been noted. Chippendale (1963) attributed to drought the partial or total destruction of such useful species as bluebrush *(Chenopodium auricomun), Eragrostis spp., Atriplex vesicaria* and *Kochia astrotrica,* although here heavy grazing had aggravated the effect of the drought. These same consequences extended to the forage shrubs, which, intensely grazed by the flocks, could not produce enough seeds for their regeneration. All these posed a grave management problem requiring an intelligent solution in a region where conditions favourable to such regeneration of the plant communities occur only once in five years.

In the arid and semi-arid regions of Argentina similar effects have been noted and ascribed to the combined effects of drought and heavy grazing. Examples are the invasion of vinal, tusca, mistol de chiva and cacti *(Prosopis ruscifolia, Acacia aroma, Castela coccinea, Opuntia spp.,* and *Cereus spp.)*, thorny shrubs of the dry savannah of the Chaco, into more humid regions of the provinces of Formosa and Chaco (De Gásperi, 1959); the spread of calden and alpataco *(Prosopis caldenia* and *Prosopis juliflora)* in the dry savannah of the province of La Pampa; and the dispersal of shrub species of the Patagonian desert in face of the disappearance of more valuable fodder species such as the perennial grasses. The research plots have been installed for some years in these regions and in the mid-west of the country but have not so far, however, allowed consideration of the partial effect of drought in this complex phenomenon (De Gásperi, 1959; Soriano, 1959; and Roig, 1968).

6.3.3 *Soil type and drought injury*

Soil type is undoubtedly one of the most important factors in the consideration of drought. Soil texture determines the water-storage capacity. The water-storage capacity of the soil and its salinity determine the potential energy the plants have to overcome to absorb water. All these, together with soil fertility, determine the extent of root development which has so much influence on the water equilibrium of plant tissues. Besides this complex influence of soil type on drought it is necessary to bear in mind that drought can affect soil type by initiating degeneration processes which are sometimes irreversible.

Description of the water capacity of soils, based on direct measurements of their hydrological constants or on intelligent approximations on a local or regional scale, is an indispensable part of the adequate assessment of drought, its régime and the planning of defensive strategy. Examples of contributions to the first type of solution to this problem may be found in the work by Bykov (1962) in the U.S.S.R., in which the hydrological and edaphic properties of more than 150 soil types in the middle Volga area are described; by Shaw and Runkles (1956) and Shaw *et al.* (1959) in the United States; and by Burgos and Corsi (1970*(a)*) in Uruguay. On the other hand, the map of water capacity for Uruguay based on a map of soil use and management in that country (Burgos and Corsi, 1970*(b)*) could be mentioned as a simple rational approximation on a regional scale.

The influence of water storage capacity on the intensity of drought is referred to explicitly in various works quoted in the bibliography, where its effects are related to soil texture. This influence is confirmed in work by Carter (1964) where the greatest extent of drought injury to shrubs in south and south-west Texas in the long dry period from 1950 to 1956 was found on the clay, silty clay loam and saline clay, while less damage was found on gravelly soils. In the same way simultaneous observations of mortality in native grasses in different soils were used by Chamrad and Box (1965) to assess their relative drought-resistance after the drought of 1961-1963. In these experiments it was found that sidecost bluestem was particularly sensitive while other species such as silver bluestem, buffalo grass and brownseed paspalum were more resistant.

The value of litter in regulating water storage in the soil by moderating the temperature, evaporation and surface erosion has been shown by many writers. Osborn (1950), after the drought of 1946-1948 in south-west Texas, reached the conclusion that, whatever the animal density, only moderate grazing should be carried on so that a certain amount of the grass might form litter sufficient to protect the remaining fodder as well as the soil. Glendening (1942) showed experimentally, using barley straw and gauze mesh on plots of 10 cultivated native grasses, that water content was greater under straw and gauze, and that the time taken to reach "wilting point" was much longer than for the bare soil in the check plot. In addition, germination and emergence was between four and twenty times better on the different treatments than on bare soil.

The extraordinary adaptation and areal development of the weeping grass *(Eragrostis curvula)* introduced into semi-arid regions of Argentina is largely due to the abundant litter formed by the lower leaves, restricting loss of soil moisture only to transpiration of the green leaves. This green foliage is the only fodder reserve in the region during drought (Covas, 1963).

Texture and fertility are important factors in root development. Although it has been shown that under drought conditions fertilizers do not increase root penetration (Burton *et al.*, 1954), their effect on perennial species in moister years can lead to a greater root development, which restores their resistance in bad years. The same writers found, in experiments with fodder grasses in the south-eastern United States, that the most drought-sensitive species had 93 per cent of their root system in the top 60 cm of the soil while the most resistant in the experiment – those of the bermuda grass type *(Cynodon dactylon)* – had only 65 to 68 per cent of their total root mass in this soil layer.

Degeneration of the soil may also be a consequence of drought. Death of the plant cover exposes the soil surface to intense radiation which dries out the upper layers and changes its biological properties. However, it is principally the action of wind and rain which begins or emphasizes the phenomena of wind and water erosion and consequent damage to soil structure. Trampling by livestock and overgrazing add an effect which is difficult to remove unless management techniques are adapted to avoid it. In this connexion one may mention work by Savage (1937) on the consequences of wind and water erosion in the Great Plains of the U.S.A.; by Chippendale (1963), who notes the effects of wind erosion in the drier climates of Australia; and by Glendening (1942) and Osborne (1950), whose results showed the importance of litter in soil conservation and the prevention of wind and water erosion. Similar effects have been noted in the east of the pampas region in Argentina and Patagonia by Weber (1947) and by the Institute of Soils and Agricultural Engineering (1948).

6.3.4 *Stocking rate and pasture use in drought injury*

Drought damage in stock-farming regions and the subjective estimate of its intensity are very often associated with the stocking rate of the area. The latter is defined as the number and type of animals per unit surface area as well as the way in which the pastures are tended. Although it is not possible to place average values on stocking rate and pasture management for general application, since these must depend on local conditions, mention of some attempts in this direction may help in understanding the complexity of the problem and shows in which direction the solutions lie. Thus, drought has a general effect on all vegetation, the interaction between drought and grazing has very different effects on each species of forage plant, and understanding of this problem is very important.

Nelson (1934), working in the semi-arid region of the United States, used 13 years of observations on the Jornadas Experimental Range in the southern part of New Mexico to check the response to drought, grazing and wear of black grama grass *(Boutelouy eriopoda)*, which he wished to preserve for its palatability and perennial properties. His study included two long droughts: 1916-1918 (three years with only 37 per cent of average rain) and 1921-1926 (five years with 60 per cent of average rain). Four grazing treatments were used: *(a)* moderate grazing corresponding to a use of 75-80 per cent of the annual growth of that species by the end of the grazing season in each year; *(b)* extreme overgrazing during both wet and dry seasons, using all the annual growth; *(c)* complete grazing in good years to the end of the growing season (85 per cent) and slight overgrazing in dry years and *(d)* as before but with grazing only in summer and autumn. These experiments showed, among other results, the following:

(a) Drought had no great effect on the density of black grama but moderate grazing produced better conditions for recovery following rain;
(b) Moderate grazing gave better results in the preservation of the species than total grazing in good years and slight overgrazing in dry years;
(c) Overgrazing during the growing period hindered recovery in wet years and such use, year after year, resulted in total destruction;
(d) The moisture of previous years had more influence on the production of each year than that of the current year.

Savage and Jacobson (1935) and Savage (1937), in Kansas, examined the effect of three management types – moderate grazing, heavy grazing and no grazing – on two species believed to be immune to drought, buffalo grass and blue grama *(Buchloe dactyloides* and *Bouteloua gracilis).* However, it was found that the greatest injury to these species occurred in climatological extremes of drought and heat. The difference in surface cover in grazed and ungrazed areas after the 1933-1934 drought, i.e. the effect of grazing alone, was only 10 per cent, although the resulting injury was proportional to the amount of grazing. It is interesting to note that, on the contrary, in some areas where the effect of drought was least, grazing seemed to favour the growth of some species such as buffalo grass. Harvesting in experimental plots confirmed these results.

Observations by Osborn (1950) in south-west Texas taken in an even drier area than above and on prairies in which the dominant species were sideoats grama *(Bouteloua curtipendula)*, curly mesquite *(Hilaria belangeri)*, buffalo grass *(Buchloe dactyloides)* and hairy grama *(Bouteloua hirsuta)* showed that an excessive stocking rate significantly decreased the stand of useful grasses in drought years. He suggested a modification to the normal regional management previously established by Jardine (1922) who had recommended a progressive and fixed decrease in stocking rate of 25, 40 and 50 per cent in successive drought years, to a variable proportional decrease depending on the recorded rainfall. He recommended using the total rainfall in the last two growing seasons to evaluate conditions in each year. In this way conditions of growth in the current year are integrated in one figure, with those of composition, density and vigour of the stand surviving from the previous season. When the rainfall varied by more than 20 to 25 per cent he recommended varying the stocking rate by the same percentage. He concluded that if stock numbers are seasonally adjusted and forage consumption controlled to maintain the litter which ensures conservation of plants and soil, an equilibrium between production and consumption of forage will be established.

Thomas and Young (1954) did a similar experiment in the drier region of western Texas. Their trial lasted 16 years with a mean stocking rate varying between one animal unit per six to 16 hectares. They found a series of relationships by which an intelligent livestock management system could be set up in regions subject to frequent drought. Analysis of the stocking rate and grazing season showed the damage caused to grass populations by high stocking rates. Heavy grazing in the spring was more damaging than in the autumn and quickly destroyed the pastures. Moreover, heavy grazing by cattle and sheep caused a decrease in some species such as sideoats, buffalo grass and curly mesquite, while tobosa grass grama increased. The relationship between the type of stock and pasture population showed that heavy grazing by sheep decreased broom seed and increased three-awn grasses, while cattle grazing decreased the population of the latter grasses and to a much less extent that of tobosa grass. The harvesting of forage to compare yields of pastures with temporary enclosures (with one animal unit per eight hectares) showed that sheep grazing removed more forage than cattle grazing and this difference was maintained in drought conditions, although the injury caused to the pasture by sheep could be greater than "spot grazing". It was shown that supplementary feeding was necessary for cattle earlier than for sheep.

In Australia also it has been shown that drought and bad grazing systems have brought about a deterioration in the pastures, especially in Central Australia. Chippendale (1963) pointed out that early grazing at "first green" prevented the formation of seed and so the renewal of species of economic value. Grazing was recommended after heading when dry matter yield was greatest. This pattern, which is not followed in sub-humid regions because of the seasonal decrease in nutritive value of the forage, is justified in arid and semi-arid regions by the preservation of the "stand" of native forage plants.

6.3.5 *Animal predators and drought*

Animal predators, herbivorous and granivorous, may be a factor directly intensifying drought injury by contributing to the destruction of the vegetation covering the soil, and of its seeds, so hindering its natural recovery after drought. In important stock-farming regions this effect has been described and has been shown experimentally in some of them. In sub-humid regions of Australia reference has been made to damage caused by rabbits and, locally, in some isolated parts of the continent, additional damage due to goats, horses, camels, wild donkeys and kangaroos has been observed (Chippendale, 1963). In arid and semi-arid areas of the United States also the depredation by some of these animals is known. The extraordinary increase observed in the numbers of the large North American hare "blacktailed jack rabbit" *(Lepus californicus)* since the droughts of 1954-1955 and 1955-1956 coincided with places where damage caused by the drought was intensified by this predator. It was shown that this increase in the population was due to the rabbits' having to abandon their natural areas by a marked drought-induced decrease in their natural pastures and having to seek new areas for expansion (Bronson and Tiemeier, 1959). This effect is also well known locally in arid and semi-arid areas of Latin America where such animals, along with the domestic animals and arid climate, are responsible for degeneration of the pastures and soil and the poor development of natural pastures. In Argentina they have been said to be responsible for the non-regeneration of some useful species by eating the seeds (De Gásperi, 1959).

6.3.6 *Artificial modification of natural vegetation in pasture management in semi-arid areas*

Changes induced by drought and poor management of pasture in those plant communities which occur mainly in semi-arid regions may be favourably controlled by suitable methods.

Control of invading weeds and thorny shrubs, as mentioned by Osborn (1950), De Gásperi (1959), Carter (1964) and Roig (1968), would favour the re-establishment of more profitable species which would occupy the space surrendered by them, especially if aided by appropriate livestock management.

Another favourable artificial alteration in the plant community consists of sowing and propagating drought-resistant species. Such an experiment has been conducted by Houston (1957) in the semi-arid regions of the western

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United States since the great dry spell of 1931-1936, when the native grazing lands were reduced to less than 20 per cent and, in places, to less than 10 per cent of what they were before the drought. The grasses which recovered most quickly were sandberg blue grass *(Poa secunda)*, needle and thread *(Stipa comata)* and buffalo grass *(Buchloe dactyloides)*, and more slowly, western wheat grass *(Agropyron smithii)* and blue grama *(Bouteloua gracilis)*. In 1938, sowings of crested wheat grass *(Agropyrum desortorum)* were commenced for comparison with native grasses of abundant spring growth, but which in maturity became coarse and unappetizing. So well did this species tolerate the competition of the native ones that at the end of 12 years' drought, ungrazed plots of this species produced 700 per cent more fodder than perennial grasses and 200 to 250 per cent of the total production of native pastures under the same conditions.

In similar regions, such as the dry Pampas in Argentina (annual rainfall between 400 and 600 mm), weeping grass *(Eragrostis curvula)* has been introduced from South Africa. This grass has been used to reclaim an area of 500 000 hectares in the past ten years. It now plays an important role in the stability of the regional livestock industry and is a valuable resource in time of drought. In the same way, a perennial wheat "trigopiro" has begun to spread in this area. It is an interspecific hybrid between *Triticum* and *Agropyron* which also has proved to be a source of forage and grain in time of drought (Covas, 1963). In the sub-tropical semi-arid climates situated more to the north, e.g. the province of Formosa, the introduction of species such as black sorghum *(Sorghum almun)* and grama rhodes *(Chloris gayana)*, notably resistant to drought, has shown the possibility of an artificial improvement to the pastures and of creating a strong reserve of essential forage in the region against drought (De Gásperi, 1959).

These may be complementary measures in the fields of conservation and improvement of local pastures in regions where it may not be economical to transfer livestock from the ranch to other regions not subject to drought, nor to provide supplementary feeding on the spot.

6.4 Animal husbandry in drought conditions

The management of livestock is just as important as the management of pastures on a scientific basis so as to stabilize and improve ranch production in time of drought.

Here it is necessary to understand the nature of the injury which drought causes in different animals and the ways of avoiding it. Determination of the effective mean stocking rate and its variations according to drought intensity are management techniques which were dealt with superficially in the preceding section. For that reason the problem of supplementary feeding which may well be the most important way of stabilizing livestock ranching in high drought-frequency areas will now be discussed.

6.4.1 *Nature of drought injury in different kinds of livestock*

The drought injuries experienced by different livestock are those arising from scarcity or lack of food and water. They are the consequence of a state of starvation which affects the bodily development of the animal and may be extended to its progeny. In cattle herds Yeates (1964) verified the quantitative and qualitative losses caused by periodic summer drought in Katherine, in northern Australia. During the dry season the cattle lost between 200 and 800 gm per animal per day up to a total of 20 per cent of their maximum weight. Similar effects were shown by Alexander and Chester (1956) and Shelton (1956). Similarly, important diurnal losses due to drought were found in South Africa and eastern Africa (Joubet, 1954; French and Ledger, 1957). Losses through animal deaths on a large scale are events well known in ranching countries. The experiments of Yeates (1964) on qualitative losses in cattle showed the changes which occurred in the muscular tissues. It was observed that drought starvation caused a lesser thickness of the muscle fibres, but not their destruction, and that the muscles could recover completely after the maximum tolerable starvation. Moreover, an increase in the proportion of connective tissue in those animals

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which suffered lack of food was shown, but this was less variable than the fibrous muscle mass. The increased toughness in the meat as a consequence of starvation is therefore explained by the increase in connective tissue.

Although these may be considered as the final quantitative and qualitative effects of drought injury to cattle, between these and their original cause there may be an escalating series of effects which, as secondary causes, may help in understanding the process and in pointing to ways of avoiding or lessening the injury. Thus, although starvation may be a consequence of drought, the effects may be aggravated by the excess energy used up by the animal in its search for food and water or by the lack of shade during drought weather. Moreover, under these conditions, animals can suffer digestive upsets through eating strange foods or foreign substances such as dung, earth, wood, etc., or even as a result of eating artificial foodstuffs inadequately prepared and administered (Southcott, 1954; Ryley and Morris, 1959). Such disorders as night blindness due to vitamin A deficiency and a loss of blood quality, decrease in haemoglobin and in the number of red cells (Southcott, 1954) have been observed.

Although drought injury in surviving cattle is reversible, as shown by the observations of Yeates (1964), it must be remembered that the consequences, in the cattle as a whole, can sometimes be carried over to the years following the drought. Thus, in intense droughts such as that in Queensland, Australia, in 1946-1947, which caused the death of more than 500 000 cattle, the greatest mortality was among pregnant and lactating cows and the survivors showed delayed heat through anoestrus (Ryley and Morris, 1959).

Injury in sheep, as in cattle, may be death through starvation, or, in less severe cases, no gain or loss in weight. Weight loss may be critical, leading to death when adult and fat animals decrease in weight to less than 40 per cent, but is recuperable when losses are only 25 to 30 per cent. In wool-producing breeds such as the Merino, however, weight losses of 25 per cent mean a considerable loss of wool, whereas weight losses of only 10 per cent will not affect wool production (Swart, 1961). In sheep, moreover, drought may cause vitamin deficiencies, night blindness, digestive disorders, and change of habits such as lactating ewes abandoning the lambs (Morris, 1956).

In spite of the seriousness of the losses which occur in adult sheep during drought, the loss of lambs is even more important and significant. In areas where drought occurs with some frequency the lamb's first month is the most critical period in its life when nutrition deficiencies cause adverse effects (Swart, 1961). This is even more apparent in breeds which develop slowly, such as the Merino, as is confirmed by work in some tropical semi-arid areas in Australia showing losses in lambs of up to 36 per cent for this reason (Franklin *et al.*, 1964).

Taneja (1955) verified the effects of drought on lambs (58 per cent twins) maintained on drought rations for six to seven weeks before weaning and six to eight weeks afterwards, in comparison with another group without this treatment (19 per cent twins). It was found in this experiment that at five months the mean weight of the lambs suffering drought was some 6 kg less than that of the control group. At 11 months the group suffering drought, when sheared, weighed only 0.5 kg less than the control unsheared but with 2.5 to 3 kg of wool. At 17 months the drought-treatment group, unsheared and with 2-3 kg of wool, weighed some 2.5 kg more than the sheared control group. Thus the greatest influence of droughts is noticed in the first five months and thereafter tends to disappear when the flock can be kept on supplementary drought rations.

6.4.2 *Livestock management in drought periods*

In ranching areas frequently subject to drought, planning of stock management is as important as that of the pastures, in order to keep production at a stable level compatible with regional economic development. Where communications and cost of transport neither allow the importing of fodder to the stricken area nor the movement of herds to areas not affected by drought, and if there is no other defensive planning against the ravages of drought, the rancher is faced with the choice of selling his stock at low prices and buying back after the drought at high prices, or of allowing them to die of hunger. Although this may be justifiable in exceptional droughts, such as those occuring once in a lifetime, it is not so when the phenomenon is so frequent as to allow its understanding through several experiences in one generation. In the first case, national or state assistance may be the only resource to allay the disaster. In the second, regional scientific experiments and rancher education through national or state extension services should provide the knowledge on which adequate individual action may be taken to reduce the ravages of drought and to relieve other parts of society of the burden of the improvidence of the ranching sector. Planning at the national level is required especially in prevention or lessening of the effects of exceptional, but less frequent, droughts, which are beyond the possible control of individual farmers and regional associations. Local and regional planning, on the other hand, is indispensible for the stabilization of livestock production in face of the more frequent droughts. If one takes as a limit the drought probability of one year in ten as that requiring protective measures by individual farmers, and that with the risk of one in 20 or 30 years as requiring national resources, there remains between these two probabilities a range of risks demanding the co-ordination of defence strategies or planning between the two levels (local and national).

6.4.3 *Fodder reserves as regional and local defence strategies*

The practice of reserving fodder against times of scarcity is as old as man's non-nomadic state. Excess fodder from one season is harvested and preserved by various methods so that it can be used in another season when fodder may be scarce.

The oldest form of conservation used has been the making of hay by drying in the atmosphere and stacking it in the field in various ways, to prevent its deterioration in adverse weather. However, this method of keeping fodder is exposed to considerable losses through birds, rodents and, at times, field fires.

With the advance of agricultural technology, other conservation systems have been brought into use, lessening or avoiding these losses and, at the same time, improving the quality and palatability of the fodder. In this way it has been possible to make use of plant species which could not otherwise have been used as valuable fodder. Among these ways of conservation may be mentioned compressing and baling, storing cut straw in silos and making pellets of various fodders and other balanced food stuffs. Baling and ensiling in different ways such as at gound level, in trenches or underground silos, are within practical reach of present-day stock farmers. Each system, nevertheless, has a definite cost according to the size of initial investment, frequency of usage during drought, losses due to rodents, insects or microbial changes and the interest on invested capital. In addition, as shown by Chandler (1958), other less definable factors affect the value of the reserve:

(a) The drought may last longer;
(b) The price of fodder bought in the normal season may be lower;
(c) The price of fodder bought in the normal season may be higher; and
(d) The urgent need for other forms of investment may decrease.

On this basis, assuming that it is necessary to decide the optimum quantity of fodder to be conserved once a year and that the rainfall of the year before does not affect the probability of drought in the following season, Chandler (1958) proposed the following equation for optimum fodder quantity:

$$C_k = c\sum_{i-1}^{k} P_i + d\sum_{i=k+1}^{n} P_i + cr\sum_{j=1}^{k}(1-P_j)$$

where C_k = cost of fodder reserve made in k months;
c = cost of fodder per unit weight (one ton is equivalent to maintenance, on drought rations, of a given number of sheep during a normal season);
d = cost of fodder per unit weight during drought;
$P_{i \text{ or } j}$ = probability of a drought longer than expected, of i or j months;
r = rate of investment interest.

In this model, the first term gives the price of stored fodder multiplied by the probability of a drought of *k* months' duration; the second term, the price of fodder which will be needed during the drought if there is not enough in reserve; and the third term, the price of fodder stored in a month when it was not needed multiplied by the probability that it will not be needed. This model gives the minimum cost of sheep fodder in New South Wales at different rates of interest and according to current prices in normal and dry seasons in the region. Thus, the minimum cost with an interest rate of five to ten per cent occurs in the six months when the farmer can keep the reserve for this length of time. On the other hand, at an investment rate of 20 per cent a reserve of no more than two months is economically justifiable, and at a rate of 50 per cent a reserve is not justified. In spite of these results, Morley and Ward (1966), also for Australian conditions, found from an analysis of local prices and lower charges that conservation could be economic for up to ten years; with usual or higher rates, this period decreased to five years. These charges included the cost of storage, insurance, fodder deterioration and interest on capital.

Afzal *et al.* (1965), in Kansas, prepared three mathematical models for the optimum fodder reserves for cattle. The first model gives the reserve to maintain the animals at their original weight with a provision for selling some cattle during the drought should the reserve be inadequate; the second, the optimum reserve to maintain weight with provision to buy additional fodder if the reserves fail, and the third, optimum reserves for only survival rations with purchase of extra fodder. The parameters of these models were estimated costs and revenues. Among the first were costs of buying or producing fodder, storage and deterioration, penal costs (if it were necessary to sell animals, buy extra fodder, or to cut down the ration below that for weight maintenance) and the additional costs (interest rates, insurance etc.). Among the revenues, the models included details of benefits from saved fodder, revenue from animals sold because of shortage of foodstuffs during the drought and from production – the weight gain in the animals if there is no drought in the period. From this study, it is possible to show that by applying inventory analysis it is possible to place at the farmer's disposal various strategies for achieving his objective which is, in the long term, stabilization of production within the more frequent climatic fluctuations of the region.

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CHAPTER 7

DROUGHT AND WATER REQUIREMENTS

7.1 Introduction

Hydrological practices and structures can be used to lessen the impact of drought. Reservoirs are planned to meet the demand in drought years, while evaporation suppression can be practised in order to prevent reserves from dwindling so rapidly. Wells and boreholes may be deepened to tap sources of groundwater at greater depths, river intakes can be lowered and schemes initiated which use flood waters for groundwater recharge. These and other measures can help alleviate the effects of drought on domestic, industrial and agricultural consumers. Yet during drought, where there is competition for supplies, it is invariably agriculture that suffers some of the first restrictions on water use, and this at a time when the demands of agriculture are usually greatest. For areas where domestic and industrial consumption is minimal, it often arises that agricultural water supplies are poorly organized to cope with drought.

An agricultural system represents the human response in space and time to a wide range of physical factors, coupled to those of a socio-economic nature. Weather and climate are some of its more important controls, especially their relevance to water-soil-crop relationships. In some parts of the world agriculture has had a considerable time to adjust to its physical constraints, but in others, more recently settled, the vagaries of climate can upset practices established over short periods. Such areas are particularly susceptible to drought, despite increasing use of weather-resistant crops and greater reliance on weather forecasts for management (Sewell, Kates and Phillips, 1967). Nevertheless drought can also be a hazard where agriculture is more intensive and more advanced and has had a longer time to evolve. Narrowing profit margins, greater specialization and mechanization, and the demands for an ever increasing production per acre make the agriculture of these regions more at the mercy of climatic aberrations than hitherto (Chorley and More, 1969). Of course, water quality as well as quantity is an important consideration for most agricultural purposes and it is also a feature that is likely to suffer during drought. The principal uses of water in agriculture are:

(a) Drinking – livestock;

(b) Cooling – milk, buildings (air conditioning);

(c) Washing – livestock, vegetables, premises;

(d) Crop spraying;

(e) Frost protection;

(f) Irrigation – outdoors, glasshouses.

Obviously crop spraying and frost protection are specialized uses that need not be considered in the context of drought. Use of water for washing and cooling is largely confined to commercial systems of agriculture. On the other hand, the watering of livestock and crops is as basic to primitive subsistence farming as it is to advanced intensive systems.

7.2 Water required by livestock

The amount of water required by livestock varies from one region to another and on the moisture content of the herbage consumed. Including herbage moisture, under favourable conditions of climate, the requirement by dairy cattle is about 136 litres per day (Table XIII), of which up to 46 litres are actually drunk (Maclusky, 1959). Depending on the type of animal and condition (whether lactating, pregnant, etc.) stock can tolerate drinking water with a total salt content two to ten times higher than can humans (1500 ppm). Drought-induced reductions in quality, such as by bacterial contamination, increase the likelihood of infectious diseases (Powell, 1964) and reductions in the quantity of water cause loss of output, loss of body weight and eventually death.

TABLE XIII

Water consumption by livestock in the United Kingdom
(Prickett, 1970)

Livestock	*Consumption of water*
Dairy cows	136 litres/head/day
Other cattle	46 " " "
Sheep and lambs	7 " " "
Pigs	14 " " "
Poultry	0.2 " " "

Appreciable amounts of water are required for washing down housing and yards, a maximum of about 70 litres per cow per day being needed for power-hose cleaning. In some circumstances pollution of small streams may follow such operations under drought conditions. More susceptible to drought are the systems employed for air conditioning, as these tend to be closed down when reserves of water are dwindling rapidly. Air-conditioned barns are used for housing dairy cows, in some of the hotter parts of the world, in order to improve milk yields during summer. Studies of the expected decline in milk production have been made for the United States (Hahn and McQuigg, 1970). Losses that might arise during an average summer in the absence of air-conditioning range from less than 25 kg/day in the northern United States to over 340 kg/day in southern Texas (Figure 10). During drought this decline in production is likely to be even more marked and may attain twice or three times the average loss of output.

7.3 Irrigation systems

Irrigation systems are characterized by considerable variety in scale, complexity and refinement. Likewise their physical environments and economic and social settings show marked differences. The flooded rice fields of many parts of Asia, the cotton growing areas of the Sudan, the water meadows of medieval England now irrigated by modern sprinkler systems, the small patches of maize grown by the Hopi Indians in Arizona and similar examples from other regions of the world demonstrate these contrasts. Yet all systems have a common aim, namely the maintenance of soil moisture at the optimum level for plant growth. It is not entirely clear what the optimum level is. This is not only because of the contrasts due to the various soil types and the different crops, but also because of the non-equal availability of soil moisture for growth and maintenance of turgor between the upper and lower limits of available water, namely field capacity and permanent wilting point (Figure 11). It seems most likely, however, that this level is appreciably above permanent wilting point, but the drought-resistant properties of the plant and its rate and stage of growth are important considerations. Soil texture is significant too, because those soils with finer

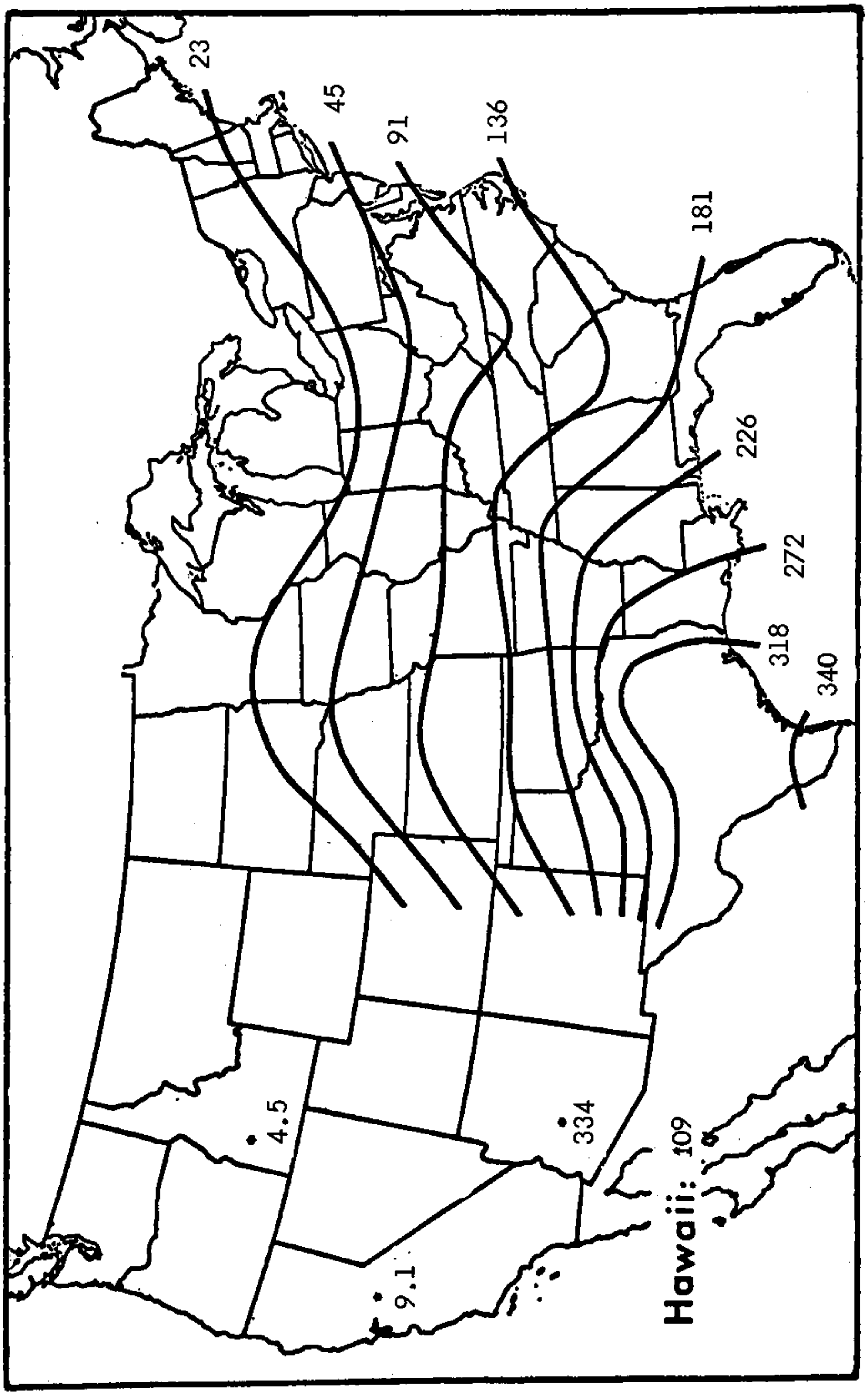

Figure 10 – Expected production losses for a summer season (kg milk/cow/season). *(From paper by Hahn and McQuigg, 1970)*

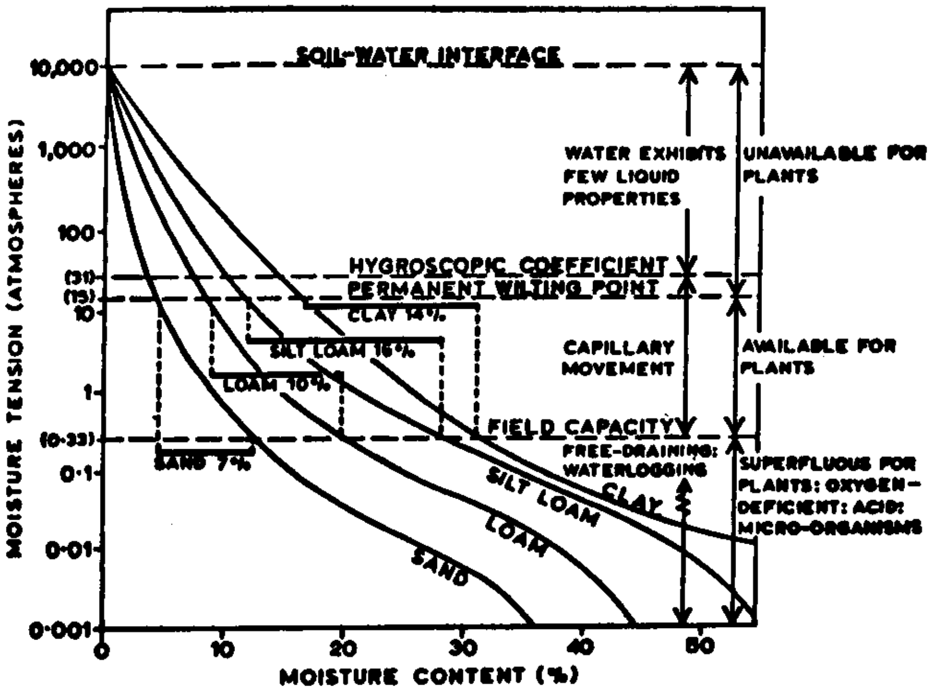

Figure 11 – The relationship between moisture content and moisture tension in four different types of soil, indicating the range of moisture available for plants *(After More, 1969)*

particles, such as silt loams, provide a greater percentage of available water. But then there is the point that the concept of field capacity is really a simplification because drainage of gravitational water, particularly in sandy soils, can continue at a very slow rate for a lengthy period after the initial rapid outflow. This gravitational water is also available to the plant as long as it is in the root zone.

Water for irrigation can come from a variety of sources, including the following:

(a) Rivers, streams and canals;

(b) Springs rising locally;

(c) Shallow wells and deep boreholes;

(d) Lakes, ponds, flooded quarries and pits;

(e) Piped supplies from public sources.

Each source is susceptible to drought to a greater or lesser degree, the least likely to suffer being those in which the water originates at a considerable distance outside the drought-stricken region. For example, a spring may be a discharge from an aquifer fed by infiltration in some distant mountains. Various steps can be taken to prepare against drought, such as increasing storage and improving supplies. Extra reservoirs may be constructed and these may be of the off-stream, impounding or groundwater seepage types. Boreholes can be deepened to increase yield and the same result may often be obtained by acid treatment or similar measures.

In many irrigation systems, few attempts are made to measure the quantity of water applied with any degree of precision. Under normal conditions, water is often plentiful enough and so cheap that there is little need to go to the trouble of measuring it, other than in very rough terms. However, where high-cost water is employed, such as in glasshouse irrigation, water is most carefully metered and applied. If equal care and attention could be given to the water economy of an irrigation system, it is probable that reserves would be greater at the advent of a drought, with obvious benefits. This is because in most irrigation practices the tendency is to apply too much water, in the absence of a rational system of management. Hence careful measurement of the volume of water used in irrigation would be one precaution that could be taken against failure of the supply during drought. But more important would be the adoption of a scientific method for determining the irrigation need. Taking the observations necessary to determine this need in and over the area being irrigated, and not some distance from it, is an essential requisite.

There are various methods that can be employed for assessing irrigation need. The most obvious solution is to measure the soil-moisture content periodically, but this involves problems of instrumentation, sampling at a number of sites and labour, and is not generally favoured. The majority of methods in current use rely on maintaining a water budget (WMO, 1968) in which the amount of soil water is determined from rainfall and evaporation. Rainfall is usually measured, but evaporation may be measured either by one of several instruments (WMO, 1966) or from weather data by one of the various formulae that have been developed for the purpose. The Penman method (1946, 1962), for example, relies on measurements of wind speed, temperature, humidity and radiation in some form or other, to produce an estimate of potential transpiration. Of course this is an estimate obtained solely by the use of weather data. No regard is taken of the soil-moisture status and the same applies to most other methods. Nevertheless, this potential transpiration estimate provides an upper limit that the actual transpiration from a growing crop can reach when its roots have an abundant water supply.

For irrigation purposes, two important questions arise (Smith, 1967):

(a) At what stage of soil-moisture depletion does the actual rate of transpiration fall below the potential rate, due to the inability of the plant to extract moisture rapidly enough?

(b) How far has the soil moisture to be diminished before growth is checked?

Neither of these questions has been answered completely, but it is to be expected that if transpiration is checked to any great extent, plant growth and development will suffer. The accepted practice in some parts of the world is not to allow the soil moisture to fall below half the quantity of the maximum available water within the crop's root range. This amount is often termed the readily available water. It may represent, for example, a deficit of between seven and 12 cm of water under a grass crop in south-east England (Pearl, 1954). When a deficit of this magnitude is being approached during drought, the problem is to know what action to take. One solution would be to continue irrigation at a rate sufficient to maintain the soil-moisture content just above this threshold, in the expectation that the drought would break before the supply of water failed. An alternative might be to reduce the application rate, so that the soil-moisture content fell below the 50 per cent level. Water would then be conserved so that irrigation could go on over a longer period, but at the cost of a reduced yield. There are obviously other courses of action, such as fully irrigating only part of the crop, but in this and similar decisions economic considerations become increasingly important. However, likely financial losses need not necessarily be taken into account in deciding irrigation policy during drought. Decisions on what measures to adopt may also be based on statistical estimates of the probabilities of rainfall or irrigation needs of certain magnitudes for the period in question. Forecasts of rainfall can be equally valuable, particularly if they are quantitative and/or give the probability of rain.

Precipitation probabilities for one-, two- and three-week periods throughout the year were assessed for part of the central United States by fitting the incomplete gamma distribution to about 54 years of records at 125 stations (Shaw, Barger and Dale, 1960). The results of this study and similar ones, particularly the information about the probability of no rain (Figures 12 *(a)*, *(b)*, *(c)*), would be valuable for deciding how to irrigate during drought. Information about the irrigation requirement itself might be more useful. In fact, in Canada, the probability

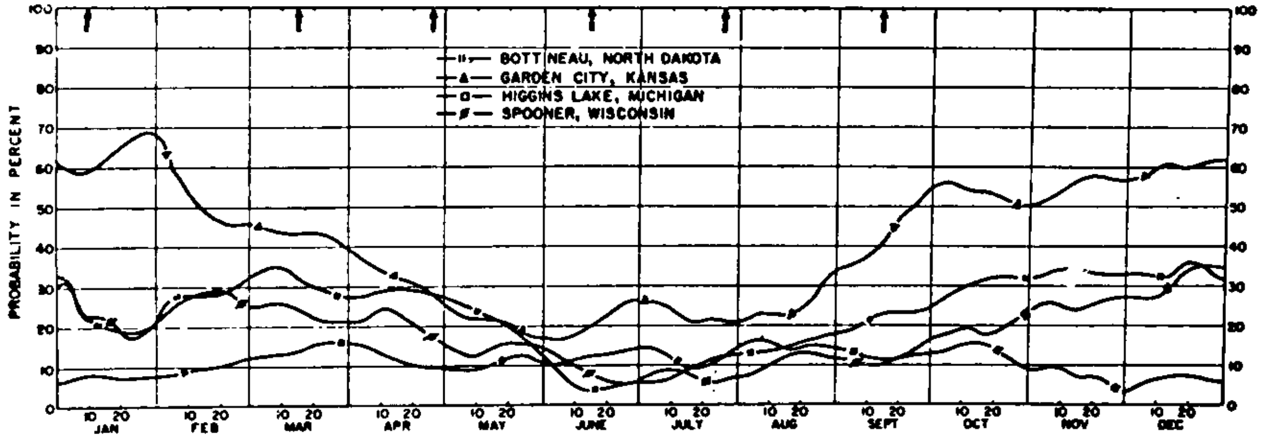

Figure 12 *(a)* – Probability of receiving only 0 or trace precipitation in one-week intervals

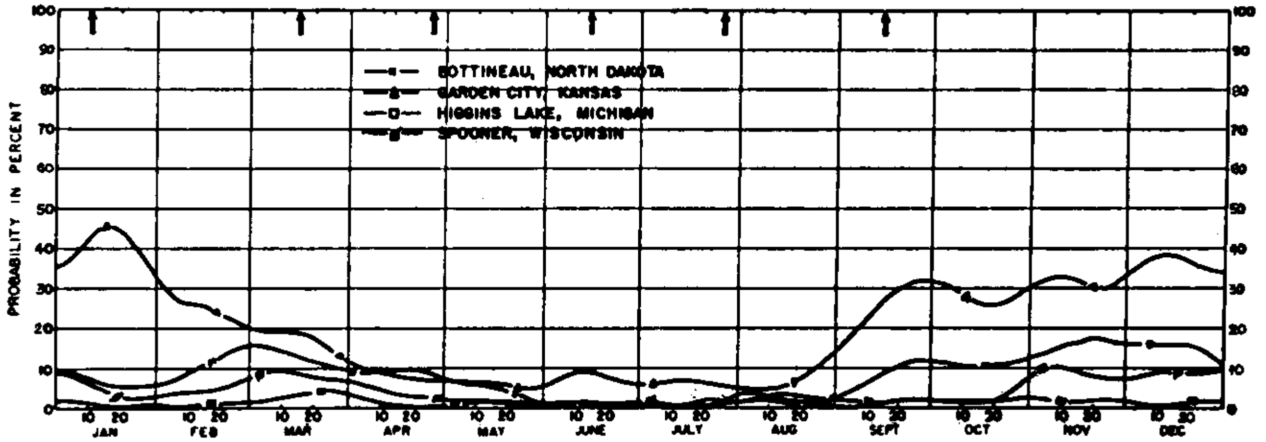

Figure 12 *(b)* – Probability of receiving only 0 or trace precipitation in two-week intervals

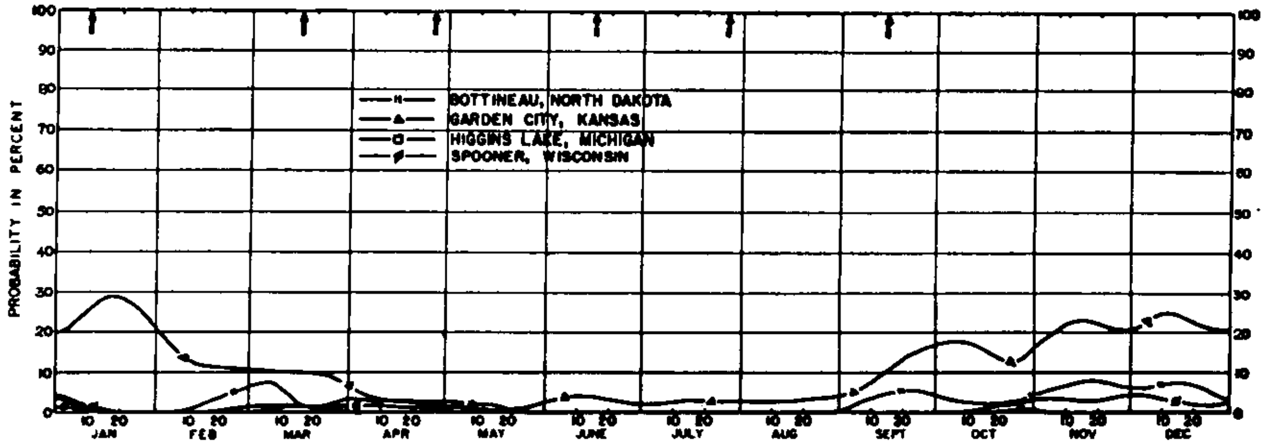

Figure 12 *(c)* – Probability of receiving only 0 or trace precipitation in three-week intervals (expressed as the percentage risk) of a particular irrigation demand being exceeded was established for weekly periods for 59 locations (Coligado, Baier and Sly, 1969). Six levels of readily available water (storage capacity) and three levels of actual to potential transpiration ratios (consumptive use factors) were taken into account (Table XIV) for calculating a daily soil-water budget from daily rainfall and potential transpiration data. From this type of table, the likelihood of a certain level of irrigation need could be established for the weeks ahead and this would be most useful in deciding irrigation policy during drought.

TABLE XIV

**Weekly and seasonal irrigation requirements (mm)
for a given risk. Swift Current, Canada. Storage capacity 100 mm; consumptive use factor 0.75**

Week beginning		*Lowest estimate*	*Per cent risk of exceeding value*								*Highest estimate*
			75	*50*	*25*	*20*	*15*	*10*	*5*	*1*	
Month	*Day*										
4	30	0						3	3	3	0
5	7	0				3	3	3	3	5	0
5	14	0			3	3	3	5	5	8	0
5	21	0			3	5	5	8	8	13	8
5	28	0			5	5	8	10	13	20	15
6	4	0			5	8	10	13	18	25	25
6	11	0			8	10	13	15	20	30	23
6	18	0			10	13	15	18	23	30	30
6	25	0		3	10	13	15	20	25	36	33
7	2	0		3	13	15	18	23	28	38	33
7	9	0		5	15	18	20	25	30	41	31
7	16	0		8	18	20	23	25	30	41	28
7	23	0	3	10	20	23	25	28	33	41	33
7	30	0	3	13	20	23	25	28	30	41	30
8	6	0	5	13	20	23	23	25	30	38	33
8	13	0	8	13	20	20	23	25	28	36	28
8	20	0	5	13	18	20	23	23	28	33	25
8	27	0	3	10	15	18	20	23	25	30	25
9	3	0	3	8	13	15	18	20	23	28	18
9	10	0		5	13	13	15	18	20	25	20
9	17	0		5	10	10	13	15	18	23	18
9	24	0		3	8	10	10	13	13	20	18
Seasonal		0	114	165	216	229	244	262	290	340	320

One problem with these approaches is the fact that droughts exhibit persistence in some areas. There may be a tendency for the observed number of long dry periods to exceed the number predicted by theory, for example, by binomial theory (Brooks and Carruthers, 1953), by Markov chain models (Weiss, 1964) and random models (Fitzpatrick and Krishnan, 1967), although the latter two methods produce improved fits. Hence it may be appropriate to try to take persistance into account in predictions of the magnitude and probability of irrigation need or soil-moisture deficit that are made for periods of drought. This was the aim in one study of drought undertaken in south-east England (Rodda, 1965). Daily soil-moisture amounts were calculated for 21 years from a water balance and the probability determined of a given soil-moisture deficit continuing for a certain number of days. The same type of approach was tried by Hashemi and Decker (1969) as one of four possible methods of irrigation management that they simulated. A 30-year series of daily soil-moisture observations was calculated which was then employed in tests of the different methods of management as follows:

(a) Irrigate to field capacity whenever there is 50 per cent or less of available moisture;

(b) Irrigate to equal the evapotranspiration amount for the expected length of the dry spell; the expected length being determined by the method proposed by Neumann (1955), using material by Feyerherm *et al.* (1965);

(c) Delay irrigation if the precipitation probability forecasts show that enough rain is expected to raise the available moisture above the 50 per cent level;

(d) Irrigate judiciously, the amount of water and its time of application being determined from short-term precipitation forecasts.

Results of this exercise (Figure 13) show that the first of these treatments required the greatest use of water, while the fourth needed the least. Such a treatment would result in saving irrigation water with no reduction in yield – a most valuable attribute during drought.

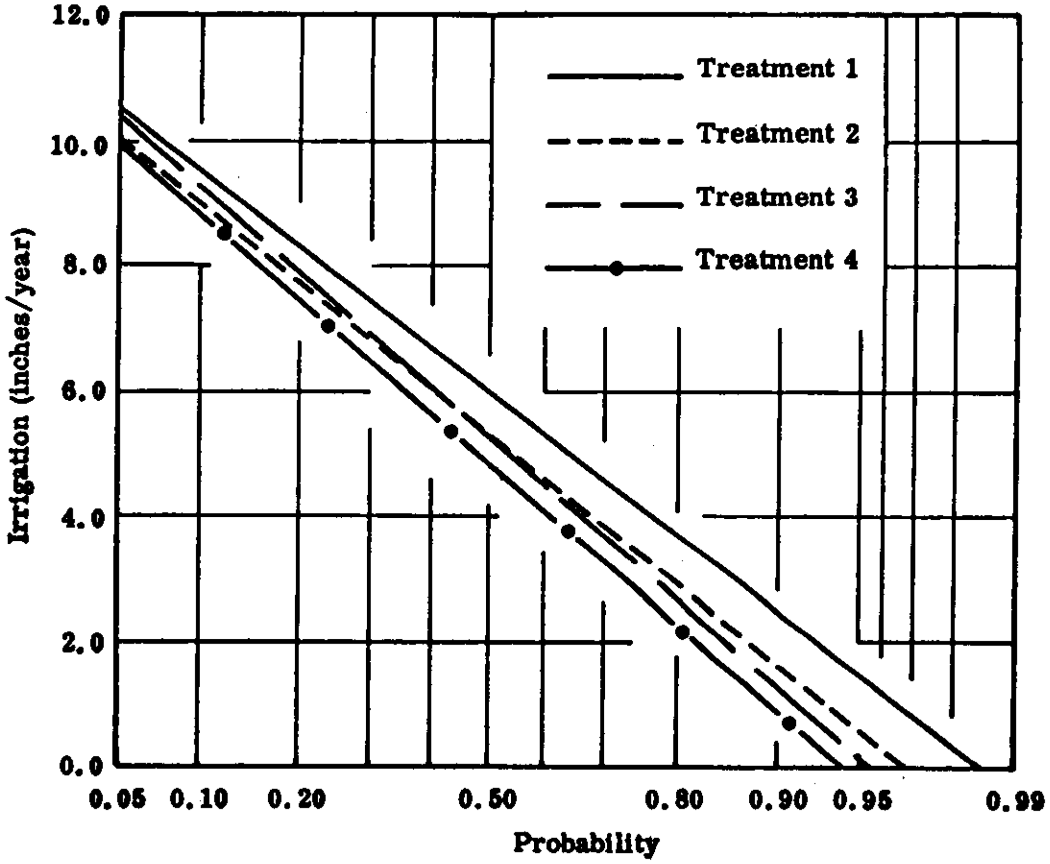

Figure 13 – Probability of requiring more irrigation water than the indicated amounts in any one season. (One inch = 25.4 mm). *(From paper by Hashemi and Decker, 1969)*

7.4 Streamflow

This discussion has so far been concerned very largely with rainfall, evaporation and storage characteristics in relation to drought, but the hydrologist has studied streamflow-drought relations to a far greater extent. Initially these studies were almost solely aimed at reservoir design for water supply, but in recent years their scope has broadened into the wider field of water-resources management.

Early design practice was based on a consideration of the driest period experienced, but the duration of a drought and its probability of occurrence are as important and this had been recognized subsequently. One of the simplest techniques is to construct a flow-duration curve for the river in question (Figure 14). The lower end of this curve expresses river flow characteristics during dry weather, but it conveys no idea of the sequence of flows nor of the duration of low-flow events. An alternative is to analyse the low flows over a given number of consecutive days and to estimate the recurrence interval of these events (Velz and Gannon, 1960). This analysis is repeated for various periods of consecutive dry days to build up a series of curves (Figure 15). Another method is to use one of several frequency distributions to describe the probability of the magnitude of low flow. However, the existence of a lower limit is a factor that is of importance in the choice of a distribution, a factor that need not be considered in relation to flood analyses. Several distributions take this lower limit into account, for instance Gumbel's limited distribution of the smallest value (Gumbel, 1954) (Figure 16), the three-parameter log normal and the Pearson type III. Matalas (1963) showed that the first and last of these fitted the data equally well and were more representative of the probability distribution of low flows than the others that he examined.

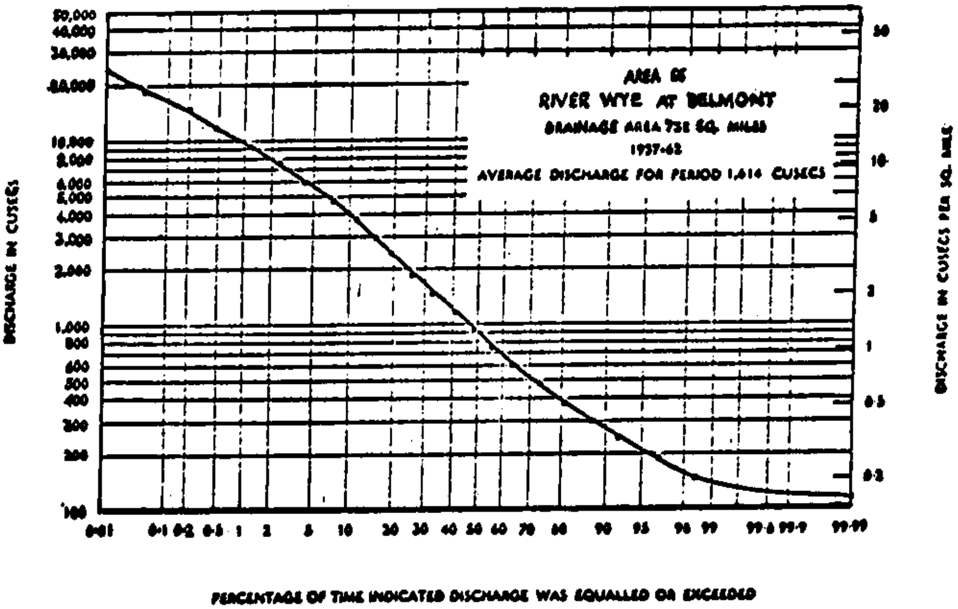

Figure 14 – Droughts, River Wye at Belmont

The fact that many records of streamflow are too short to permit an extensive analysis has led to the development of methods of synthesizing data. One simple method is to establish relations between the short-period station and one that has been in existence for much longer. The relationship may be graphical or mathematical and it is assumed to apply to low flows, their durations and probabilities. The required degree of association between stations has been investigated (Fiering, 1963) as well as the reliability of a variance estimate produced from an augmented sample, such as extended river-flow records (Gilroy, 1970).

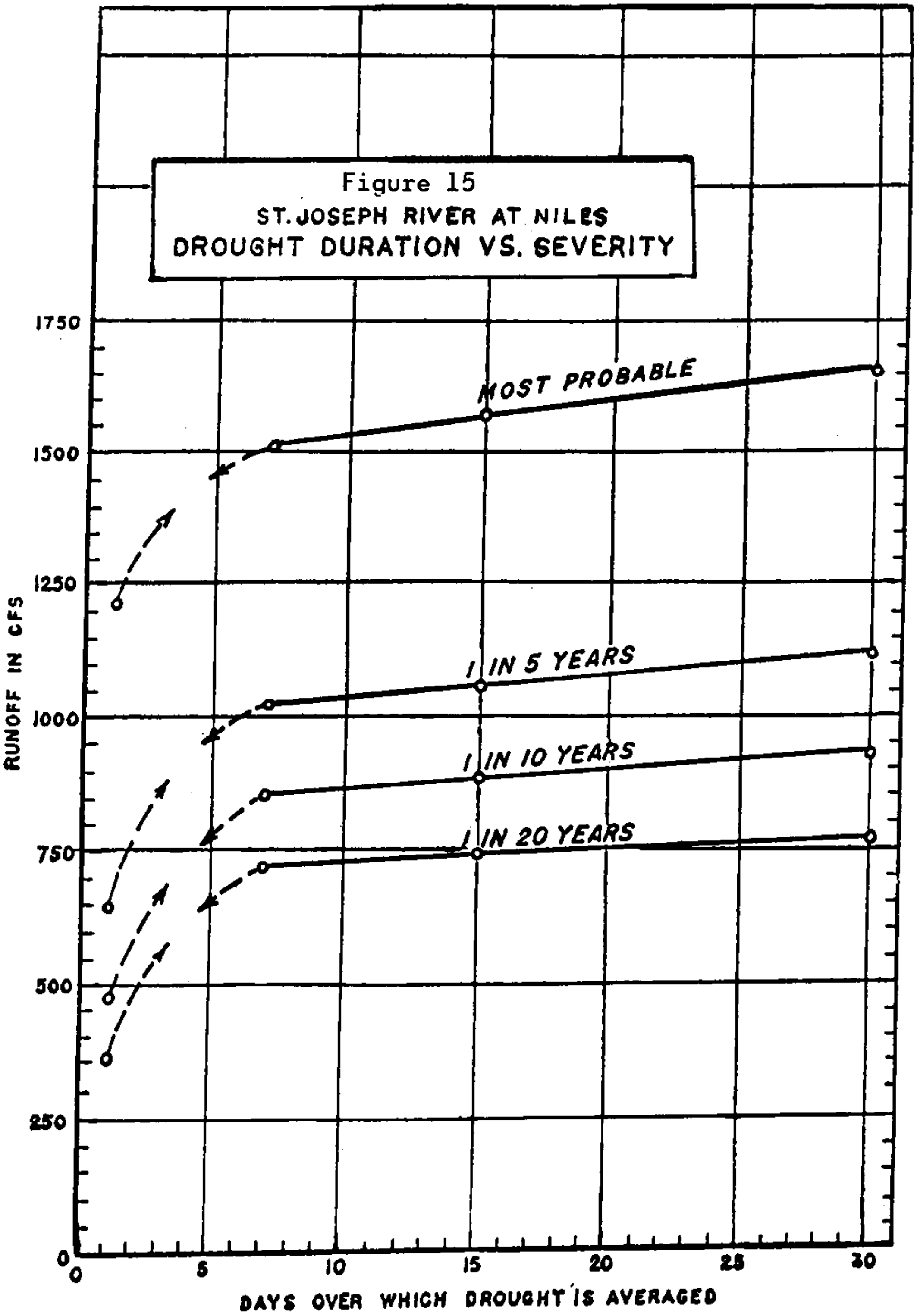

Figure 15
ST. JOSEPH RIVER AT NILES
DROUGHT DURATION VS. SEVERITY

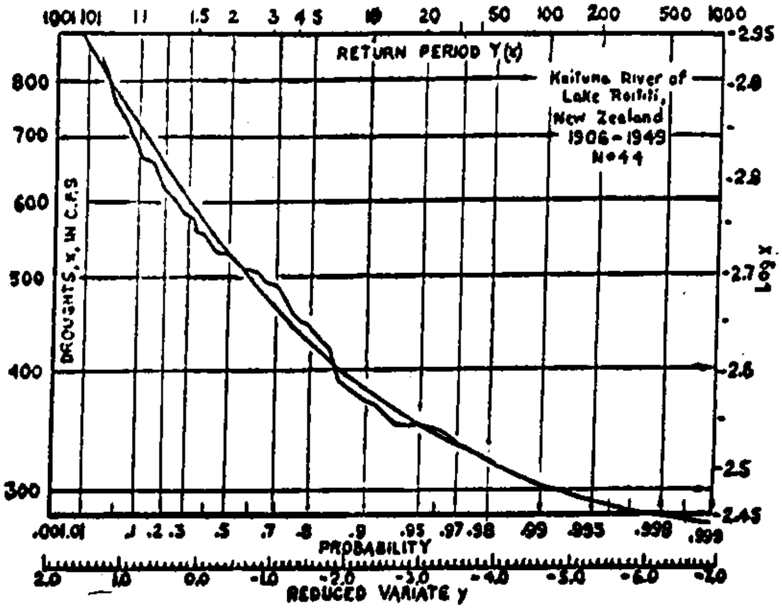

Figure 16 – Droughts, Kaituna River at Lake Roititi, New Zealand

In contrast to this very simple type of approach, there are the methods of streamflow simulation which treat discharge as a stochastic process. Stochastic modelling for streamflow simulation was first discussed in detail by Thomas and Fiering (1962) and later by Fiering (1967). Many of the studies of this type have been based on establishing the Markov property for the flows concerned (Moreau and Pyatt, 1970), annual, monthly or daily. More recently precipitation data as well as flow records have been employed in the simulation (Bonne, 1971). These generation techniques have also been applied to the assessment of the period that is the most critical drought (Askew *et al.*, 1970) for the system concerned. Of course deterministic modelling is an alternative to stochastic modelling, although more attention has been given to high rather than low flows. There are numerous examples of models of this type which have been used to study catchment behaviour, one of the first being devised by Crawford and Linsley (1966).

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CHAPTER 8

DISEASES AND PESTS IN DROUGHT

8.1 General

This account is written mainly from the viewpoint of drought associated with irregular distribution of rainfall in many parts of the world, and not from that of consideration of desert or arid areas subject to lengthy rainless periods.

The effects of drought, especially if prolonged, are generally considered adverse to agriculture. This is of course true, but drought has a measure of compensation in almost eliminating economic losses from some diseases and pests.

Most attention will be focused on diseases and pests as they affect vegetative growth, but a few animal diseases exist, the incidence of which is affected by drought, and these are briefly considered.

It is stressed that this is essentially a brief survey of a very wide subject, and the few references which are given are an indication of the wide range of relevant literature. Like many other biological/meteorological problems, considerable work has been done on the physiological side, but the amount of reliable field work is very limited.

8.2 Pests

Dry weather has more effect on population changes and survival of some pests than others, and probably most affected are the leaf-feeding insects and those insects part of whose life cycle is spent just below the soil surface.

Apart from the fact that aphids feed directly on plant nutrients, they are also responsible for the spread of certain virus diseases, e.g. lettuce necrotic yellow virus. Drought is usually associated with high temperature and low humidity, conditions generally less favourable to the development of aphid populations. The aphid population is therefore reduced because of the meteorological conditions and the reduced crop and weed growth (Geard, 1970, priv. comm., Department of Agriculture, Tasmania).

The timing of drought is important. An early summer or late spring drought can cause weeds or grasses to die off early and force aphids to develop the winged stage and migrate to crops earlier than they would otherwise. Crop plants can in this way be more heavily infected. This effect is documented for the case of barley yellow dwarf virus in cereals in California by Oswald and Houston (1953).

Many aphids have alternate hosts, and the apple-grass aphid, for example, goes from grass to orchards in late summer. Drought at some time a few weeks before this movement will dry the grass and reduce populations going to the orchards. The damson-hop aphid, by contrast, migrates in early summer from trees to hop plants. In the spring colonies tend to concentrate at the tips of actively growing shoots of the host plant. Drought during late spring may reduce or stop shoot growth, with the result that the food supply is exploited more rapidly, the migration period is shortened, and control of infestations on hop is simplified. However, the relationship between populations and host plants in drought is complex. One effect is that less woody growth, more crowding and the high temperatures usually associated with dry weather (and in some cases more rapid biological processes) might lead to a population explosion. A side-effect of drought is to increase the amino-acid content of leaves and improve nutrient and attractiveness of plants; this factor of improved nutrient may well be more important to population increases than the hot weather which usually goes with drought. The result therefore can be again to increase populations; the drought level is assumed not to be so intense as to constitute a direct threat of population survival. A further benefit to aphids of dry weather is that certain diseases such as *Entomophera* are inhibited because moisture is required for successful germination.

In general, plants stand to suffer more from aphid activity in drought than in wet weather; this tendency may be heightened by the water-stress weakened plants possessing less ability to withstand attack. A slow-moving crop may be held back at the susceptible young growth stage for a longer period, and late insect immigrants may still find the plant attractive in nutriment; the period of risk for the plant will therefore be longer. A final consideration is that aphids may sometimes be washed or splashed off plants in heavy rain; this obviously cannot happen in drought but the probability may still exist during this period from irrigation spraying..

White (1969) correlates outbreaks of psyllids in Australia with increasing high levels of soil-moisture stress and refers to the suggestion by earlier workers that plants suffering water stress may be more susceptible to attack by insects than unstressed plants. Bark-beetle outbreaks are commonly quoted examples, usually with the interpretation that drought has reduced the volume and flow of resins and so prevented the tree from mechanically excluding the beetles attempting to invade it. Although this may be a contributory cause, recent work supports the view that these attacks are in fact correlated with the amount of nitrogen available for the invading insects.

According to White, there have been many other hypotheses proposed to explain the resistance of plants to insect attack, most based on the idea of changes in phagostimulants and repellants. These substances clearly play a part in restricting host range and feeding response of many phytophagous insects. But it would seem probable that nitrogenous food – a prime requirement for all young rapidly growing animals – is more likely to be a general limiting component in the environment of phytophagous insects than any of those more specialized substances. The important aspect in the drought context is the postulation that the physiological stress of plants due to water shortage increases the amount of nitrogenous food available to invading insects, thus greatly increasing the chances of young surviving and reproducing.

A similar case involving a lengthened period on the plant is that of the larvae of gall midges of cereals. These larvae do not leave the cereal ear unless it is moist. In drought conditions fully fed larvae accumulate on the plants. After rain they drop to earth in very large numbers. Whether this movement is gradual or sudden, early or late, may therefore depend on drought conditions. The larvae will burrow to 2 cm or more depth within a couple of hours, but if drought returns, desiccation of pupae will follow (especially if hot) and high mortality will occur.

Drought also has an important influence on the activity and survival of the sorghum midge (*Contarinia sorghicola* (Coq.)). The midge survives between seasons as fully grown maggots in diapause within damaged florets, mainly in trash in fields. Under field conditions these mature maggots will readily pupate and then emerge as adult midges when suitable weather conditions occur to initiate their development, i.e., thorough wetting of the soil followed by a fortnight of high humidity. If these conditions do not occur, as in long periods of drought, it has been demonstrated experimentally that the maggots may remain in diapause up to five years and resume their normal development when suitable meteorological conditions occur (Priv. comm., Queensland, Dept. of Primary Industries).

Eelworms are strongly affected by drought, in that free movement is not possible without water. In dry soil therefore they can become almost completely desiccated, but recover from this state of suspended activity when drought ends; eggs rely upon moisture for hatching, but they too can remain undamaged for considerable periods of drought.

The biology of the cereal beetle, *Desiantha caudata*, is typical of a number of soil-borne insects (Allen, 1969). The larvae are soil-dwelling insects which damage cereals by eating the swelling seed soon after sowing or by attacking young seedlings or tillers, causing them to wither and die.

Eggs are laid singly in the soil only under moist conditions. They also hatch only under moist conditions with temperatures above 8°C but they will remain viable for two to three months under cool conditions provided the soil is moist. Larvae spend their entire life in the soil and are sensitive to moisture conditions. Adult beetles live on the surface under the protection of rocks etc. and require moist conditions. A high mortality rate occurs under dry conditions. The survival of adults through the summer months is necessary for maximum autumn egg production, hence survival is threatened under summer drought conditions.

Many species of beetle and fly spend part of their life cycle as eggs or larvae below ground, and drought at this time causes high mortality in many cases. Examples include the leatherjacket (crane fly), which suffers severe egg mortality with late summer drought or larval mortality after hatch in early autumn drought, though the spread of oviposition and hatching blurs distinction between the two periods. The Colorado potato beetle can suffer mortality in hibernation because of spring or early summer drought, and later at the egg/larval stage in summer; the insect may also suffer in larval and adult form on plants because of shortage of food in severe drought. The question of depth of hibernation arises with the Colorado beetle, and in dry soil the insect digs more deeply. Other pests such as wireworms and slugs also dig more deeply in dry weather to reach a moist layer (WMO, 1974).

Grasshoppers and droughts are often associated with each other; however, the effect appears to differ from area to area. In Canada, grasshopper plagues usually occur during periods of drought in the wheat-growing areas of the prairies. It appears that the population of the insect builds up over a series of hot, dry summers, mainly because eggs and nymphs escape damage by parasites and diseases which develop during cooler, wetter conditions. There is evidence that severe drought can kill grasshoppers, e.g. in South Australia in 1940 (Birch and Andrewartha, 1941), when most grasshoppers died before reaching the egg-laying stage, thus bringing the outbreak to an end. However, this probably does not apply to the migratory or desert locust, which is able to travel great distances; in fact the species survives by its nomadic habits which give it the opportunity to move to favourable conditions.

Meteorological conditions play a vital part in the life cycle of the locust, particularly in its early phases. The locust egg is laid, often under arid conditions, with a limited water content so that further development depends on the presence of soil moisture. This is also required to initiate vegetative growth to provide for fledgings before they can become airborne (Rainey, 1963).

There will probably always be a tendency for locust plagues to perpetuate themselves (Kraus, 1958; Rainey, 1969) until swarms receive a major setback through the simultaneous occurrence of unfavourable weather conditions during one or several seasons, over the whole of their distribution area. This appears to have happened in 1918 and 1932-1933, which were serious drought years over the North Africa–Middle East–India locust zones.

Many animals are drought-hardy for life (such as lizards and ticks) and others only seasonally; thus the lucerne flea requires very moist conditions for most of its life, but its eggs are drought-hardy.

The life cycle of the pasture cockchafer depends very much on the incidence of rainfall (Birks and Allen, 1969). Adult beetles, which are active in summer, require soil moistened to about 15 cm to stimulate egg-laying activity so that during drought conditions laying is restricted to favoured micrometeorological sites. Larvae appear in early autumn but will die under dry conditions; in fact the duration of an autumn drought largely determines the severity of cockchafer outbreaks from year to year.

One of the most serious crop and pasture pests in Southern Australia is the red-legged earth-mite *(Halotydeus destructor)*. Eggs normally withstand hot, dry summer conditions and hatch during the autumn after being in contact with free moisture for about two weeks under temperatures below 16°C. Thus poor opening rains result in reduced hatchings.

Many insects such as moths do not react in a very obvious manner to drought as such. There is a biological response to the associated warm, sunny weather when population increases occur and, provided suitable food is present, they flourish. Caterpillars and leaf-eaters generally show no very strong reaction to drought (not being affected by the quality of nutrient) but wilted plants may be left in mass migration. Some insects are equipped to withstand extraordinarily dry conditions; larvae of the moth *Ephestia*, for example, can survive in flour oven-heated at 105°C and stored in a desiccator over strong sulphuric acid.

The effects of some parasites are accentuated in drought periods. For example, heavy concentrations of ticks may build up where cattle are forced to congregate for feed and water. Their effect on drought-weakened animals, together with the additional mustering required for treatment, may increase mortality. On the credit side, during drought periods ticks may disappear from areas marginal for their survival.

Confining of sheep to small areas for supplementary feeding also encourages the spread of blowfly attacks on sheep. The incidence of strike ranges from widespread, sporadic outbreaks to severe localized attacks; poorly conditioned sheep are more prone to attack than healthier animals. Drought-breaking rains are usually followed by severe outbreaks of fly strike. Bush flies may also worry animals and sometimes reach plague proportions during drought.

If droughts are preceded by conditions favourable for the development of internal parasites then there may be considerable losses in young cattle and sheep when the plane of nutrition falls. During droughts, concentration of stock on areas favourable for survival of parasites, e.g. near bore drains and waterways, may result in continued propagation of internal parasites (Priv. comm., Queensland Department of Primary Industries).

As already stated, the timing of the period of drought can be very significant. Early summer drought may reduce seriously populations of particular insects through food shortage, but numbers can quickly be made up later. Late drought and big population reductions, however, would preclude recovery of the insect populations in that year. Most of this discussion on drought assumes that the summer half of the year is under consideration – in winter, drought is seldom of great importance for the consideration of insects and diseases because this is a period of quiescence. However, the depth of snow on shallow soil in colder climates may be very important for controlling temperatures. The lack of snow in a dry winter may cause high pest mortality because of very low soil temperatures.

An interesting effect of drought is to increase the amount of abrasive dust blown about in the air in many areas. This can cause damage to plants, and whereas some pests, such as scale insects, are more or less plugged into the plant and are unaffected, many of their predators or parasites may be injured or killed, or suffer from reduced food supply.

Drought may have important effects on control measures to be taken against pests. Chemical insecticides may have to be applied more often to a plant to control pests which remain longer than usual, and possible side-effects by the chemical on the plant may be greatly aggravated by water stress. The use of pathogenic sprays may also be drought-affected, because many of the bacteria being sprayed need moisture for sporulation. The efficiency of systemic insecticide applied to the soil tends to decrease in drought conditions even though much of the insecticide may be present in the soil; as soon as it rains, the insecticide is again taken up by the plant, and insects that have established themselves in the meantime may then be killed.

8.3 Animal diseases

Apart from considerations of whether animals can get adequate food for their development, several diseases have some relationship to rainfall amount, often in its effect on soil moisture. With dry soils there is usually much less opportunity for development of diseases or pests inimical to domestic animals. Drought therefore potentially plays a part in reducing the incidence of some diseases.

The severity of outbreaks of the parasitic disease liver fluke in sheep was found many years ago to depend mainly on wetness in late summer. This is because the flukes spend part of their life cycle in snails, which are much less numerous if the ground is dry, and because of the greater mortality of fluke eggs in dry weather. Drought in late summer strongly decreases subsequent incidence of disease.

Gastro-enteritis in cattle, associated with larvae of worms among grass, has its main periods of incidence in early and in late summer. In early summer, outbreaks are more widespread following dry conditions in the previous late summer and early autumn, whilst dry weather in mid- and late summer leads to further outbreaks. Strictly, the moisture of the soil is the main factor in this context, but drought conditions in any summer month usually lead rapidly to suitable soil-moisture deficits.

The spread of foot-and-mouth disease has also been related to both wind and rain, and for widespread dissemination of the disease wash-out of the virus (however carried) by rain seems essential.

8.4 Plant diseases

The mechanism for spore dispersal at the source point is partly dependent on weather, largely through the splashing of raindrops (the same effect can be achieved by sprinkled irrigation water) and would be expected to be greatly reduced during drought.

An interesting case of spore dispersal is that of bitter rot of apples (Rotem and Palti, 1967). The spores of this fungus, formed in *acervuli*, are sticky, and under dry conditions they resist dispersal even by winds as strong as 20 km/h. But as soon as the *acervuli* are wetted by rain or sprinkling, spores are spread.

Other examples are *Anthracnose* in lettuces *(Marssonina panattoniana)* and *Colletotrichum* on beans and are, according to Geard (1970), due to fungi which have sticky spores which need to be splashed from one plant to another before spread can occur. No overhead sprinkling by either natural rainfall or irrigation thus reduces the disease incidence.

The importance of rain varies from one stage of the life cycle to another with the same disease organism. For example, with apple scab the ascospores can be discharged into the air in response to a very light fall of rain and can become established in free water provided by dew. The later conidial stage is essentially water-splashed and needs more rain to be likely to spread and establish.

Most bacterial diseases are largely (but not solely) dependent on rain splashing for dispersal and are therefore less likely to be a problem in drought. Halo blight *(Pseudomonas phaseolicola)* in beans is a good example.

Of the different types of pathogenic plant diseases, the fungi are the most affected by drought conditions. Most fungal pathogens require moisture for infection and are therefore more serious in wet weather, but there are important exceptions. Thus powdery mildews often flourish in dry weather, though sporulation may be reduced in the absence of moisture. Prolonged drought can therefore prevent massive build-up, but semi-dry weather can lead to widespread severe attacks. The downy mildews on the other hand are virtually eliminated by drought. An interesting example of the effect of dry and wet conditions on these two types of mildew has been reported from the Salinas valley in California, U.S.A., where lettuce are affected by both a powdery and a downy mildew; the downy mildew is present in cool, wet areas and the powdery mildew in hot, dry areas, but in part of the valley conditions are moderately favourable for both diseases, which can in fact occur together.

Considering drought effects on particular crops, the potato is of special interest because it is widely cultivated and is subject to many diseases. The best known, blight, which is a downy mildew, is virtually precluded under drought conditions. Common scab, however, can be severe on the tubers after dry weather in early summer, but irrigation particularly in the four weeks following the start of tuber formation will prevent infection. Potato wart disease, *Synchytrium endobioticum* (subject to quarantine regulations in some countries) is absent in drought – and indeed, based on summer rainfall, maps can be drawn of areas free from, and prone to, the disease. In contrast, plants may be more vulnerable to wilt diseases in drought, though the effects of infection may apparently be merely drought symptoms. The importance of the timing of drought is particularly well brought out by these examples: early drought may lead to severe scab, and late drought to wilt.

Scorch is another drought-associated cereal disease; affected plants show drought symptoms, but are often also infected by *Fusarium* root-rot. With wilt diseases, the effect of drought in reducing root growth usually does not encourage the fungi to develop more on the smaller root systems. A side-effect with take-all fungus *(Ophioboluo graminis* and *Cercosporella herpotrichoides)* is that autumn and winter drought inhibits rotting of infected stubble and allows it to survive longer as a potential source of infection for subsequent cereal crops.

Apple-scab infection occurs only after comparatively prolonged leaf wetness, and drought conditions in early spring will normally preclude outbreaks of the disease although, exceptionally, leaf wetness may be maintained in a cloudy moist régime without the occurrence of measurable precipitation.

These examples show that drought, especially in association with hot and dry weather, can affect not only the incidence of various diseases but can very markedly affect the ability of the fungi to infect and spread and so to cause serious losses.

Root rots reduce the ability of the plant to absorb water from the soil. Drought accentuates the resultant water shortage. An example provided by Geard (priv. comm.) concerns pea crops, where severe root rot due to attack by *Fusarium solani* and *Pythium ultimum* is common following wet conditions at sowing time. With normal seasonal conditions to follow, the effect on the crop is very significant but not severe. With dry weather the effect of the root rot is very severe.

Other root diseases, this time affecting cereals, are take-all or hay-die *(Ophioboluo graminis)* and root and stem *Rhyoctania.* These diseases are accentuated under drying conditions when diseased roots suffer from the inability to extract water from the soil (Banyer, 1966).

Some root- and stalk-root conditions are increased by dry conditions or by a succession of moist and dry periods. Stalk rot *(Macrophomina phaseoli)* of sorghum and maize is one such disease. It has been suggested for diseases such as crown rot *(Gibberella zeae)* of wheat but evidence is inconclusive.

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CHAPTER 9

LOCAL ENVIRONMENT CONTROL AND DROUGHT

9.1 Introduction

When considered in its widest aspects, the modification of weather is a very extensive field of human endeavour embracing changes on the microscale (e.g. within two or three metres of a hedge), on the mesoscale (e.g. the effect of forests), and on the macroscale (e.g. the attempts to increase precipitation by cloud seeding). It is obvious, therefore, that weather modification can have an effect on drought and its alleviation. The following paragraphs outline some of these effects on various environments.

9.2 Wind barriers

The modification of wind flow by semi-permeable wind barriers is important because of the effect on evaporation and hence on the water balance of the sheltered area. This subject has been covered in detail by van Eimern *et al.* (1964) and much of the following material has been drawn from this reference.

9.2.1 *Influence on air humidity*

Influence of the barrier on humidity varies with the time of day, weather, soil conditions and plant cover. Most investigators have found slightly higher humidity (but generally not more than ten per cent higher) in the protected area in the lee of the barrier and the effect has been observed during both day and night. It has been attributed to the normally greater soil moisture content and less turbulent exchange in the immediate lee of the barrier. Of greater relevance in the context of drought, it has been noted in the semi-arid zones and dry steppes that the differences in relative humidity of the air between sheltered and open steppe become very small because of the drying out of the soil, especially in the day-time. Differences of less than one per cent are quoted.

Rosenberg (1967) reports that absolute humidity is higher by both day and night in sheltered areas but relative humidity varies according to whether temperatures are greater in sheltered areas or in the open.

9.2.2 *Influence on dew*

The net balance of long-wave radiation from the shelterbelt, the soil and its coverage are important factors in dew formation but the air-mass properties (i.e. relative humidity, wind speed and turbulence) are decisive factors in its distribution. Because of the influence of the barrier on temperature, humidity and wind speed in both the vertical and the horizontal, dew is a minimum immediately adjacent to the barrier and increases to a maximum a short distance downwind (about two to three times barrier height). Dew forms earlier near windbreaks because the critical minimum wind speed is reached earlier.

9.2.3 *Influence on snow cover*

Because of the great influence of wind on the path of a snowflake, shelterbelts exert a very important control on the distribution of snow in their lee and in many regions where snow is a substantial proportion of the

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total precipitation, shelters are erected solely for this purpose. The actual distribution of snow depends on the wind speed and direction, specific gravity of the snow, the height, density, construction and slope of the barriers and the eddy produced. The position is also complicated by subsequent snowdrifts which cause a further local redistribution of snow cover.

Budyko (1952) says that, in climates with a dry summer, belts must be used to trap the snow in the lee and ensure as even a snow cover as possible to provide the whole ground with sufficient moisture in the spring. In all zones with long, severe winters and strong snow storms, such as the steppes on the Volga, in Siberia, and in northern Kazakhstan, the winter effect of shelterbelts is often the most important. Because of a number of factors, a wide range of results has been obtained from investigations and, although a typical distribution of snow cannot be specified, the values quoted in Table XV are similar to those obtained by a number of other investigators.

TABLE XV

Depth of snow cover behind shelterbelts in the steppes around Stalingrad (Subin, 1960)

Belt	*Depth in belt (cm)*	*Distance from belt (metres)* 10	20	40	80	100	150
Impermeable	240	240	42	35	30	28	20
Impermeable (orientation N-S)	140	130	120	100	80	65	40
Permeable (orientation W-E)	80	80	75	60	43	40	40

The denser the shelterbelt, the deeper is the snow deposit both windward and leeward of the belt, but farther downwind accumulation is lighter. More even deposits are collected behind permeable shelterbelts such as deciduous trees. Thus shelter planning can determine to a considerable extent the distribution of snow over an area and thus in turn the contribution to soil moisture from snowmelt. This may be a disadvantage in areas where drying out of the soil is necessary behind dense barriers before ploughing can commence in spring but in other parts, particularly where the supply of soil moisture is marginal, this redistribution of snowmelt can be a decided advantage. Further details on the redistribution of snow by shelterbelts are given in van Eimern *et al.* (1964), which contains a wealth of experimental details and summaries of views of experts.

9.2.4 *Influence on evaporation*

As in many studies of evaporation, it is important to differentiate between actual and potential evaporation and the respective instrumentation and any tabulation of evaporation should specify these details. Almost all investigations carried out using free water evaporimeters indicate that an appreciable reduction in evaporation occurs behind shelterbelts. However, this conclusion cannot be generally applied to actual evapotranspiration because this depends on other factors such as available soil moisture, the rate at which it is transported to the leaves and the stomatal behaviour of the plant. Table XVI compares the evaporation reduction behind a shelterbelt and in this case, as the plants exposed were adequately supplied with water, the distribution did not differ greatly from that of free water.

In semi-arid wind-swept areas where irrigation is practised much of the limitation of water supply to plant growth is removed, but evaporative demand may not be decreased sufficiently to remove all moisture stress on the plant. Rosenberg (1967) says that windbreaks can be effective in reducing evaporative demand, minimizing plant

TABLE XVI

Evaporation on a field between shelterbelts measured by different methods in per cent of control value (Golubeva, 1941)

Height 10 to 20 metres

Distance from shelterbelts (metres)	*10-12*	*32*	*50-62*	*100-107*	*152*	*200*	*300*	*(Control) 400-420*
Piche evaporimeter	70	68	77	87	98	104	97	100
Open water surface	77	–	82	86	–	95	94	100
Summer wheat from moist soil in container	78	73	–	78	106	–	–	100

water stress, and guarding against the loss of photosynthetic potential which accompanies turgor loss and stomatal closure. There is also every reason to believe that windbreaks increase efficiency of water use, i.e., food or fibre production is increased for each unit of water expended. This may be true not only in sub-humid and semi-arid regions but also in the true deserts, where oasis-type irrigation is practised.

Shelterbelts are not likely to be effective agents in water conservation in the arid zone; nor would they result in much saving under conditions of extreme drought when there is little or no soil moisture for evaporation. However, in moist climates the decrease in evapotranspiration they cause can result in a saving of 20 to 30 per cent of water, and in marginal climatic areas or in seasons when conditions become critically dry the reduced water loss may be sufficient to prevent crop failure. The technique is more adaptable to the European scale of agriculture where fields are relatively small and climates are normally moist enough to permit the establishment of well-developed shelterbelts. It is less suited to the large-scale farming of Australia, where fields are large, plant density is less and suitable tall shelters are difficult to establish in marginal agricultural areas because of the low rainfall. For example, the Mallee eucalypt scrub typically grows to less than six metres and has a widespread root system designed to make the best of the meagre stored soil moisture resulting from 25 to 40 cm of rainfall a year under very hot conditions.

9.2.5 *Influence on soil moisture*

This is closely related to the previous discussions since the amount of soil moisture depends *inter alia* on rainfall or melted snow, less runoff and the loss by evaporation. Uniformity of soil moisture is likely only at the level of field capacity and in any area where the above factors are subject to variations, whether natural or induced by shelterbelts, there will be spatial variations in soil moisture at specified depths once the soil starts to dry out.

Van Eimern (1964) quotes from a number of investigations but Table XVII from Muller (1956) is perhaps as instructive as any.

TABLE XVII

Mean values of soil moisture (as percentage of values for open field) behind a hedge on loam soil growing potatoes (based on five days' measurement)

Distance from belt (metres)	*5*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*100*
Soil moisture at 5-10 cm depth (%)	121	124	118	114	111	103	99	99	100	100
Soil moisture at 20-25 cm depth (%)	118	119	115	112	105	100	99	100	100	100

This shows significant increases in soil moisture at both levels up to 40 m (11 times the height of the shelterbelt) from the shelter and, if this relativity could be maintained under drying conditions, then some protection against drought could be given.

9.3 Modification of soil moisture by runoff/"run-on"

A very important factor for plant growth in areas subject to water shortages is the redistribution by runoff of the water which falls on the surface as rainfall. The process is not very significant in the context of agricultural drought in hilly or mountainous areas where runoff finds its way very quickly into a stream bed nor in the heavily vegetated areas of the humid zones where surface runoff is relatively low and infiltration high. An exception is the terraced hillsides of south-east Asia (Robertson and de Weille, 1973). However, in the semi-arid and arid zones the lack of surface cover, the relative flatness of the surface broken occasionally by abrupt hill faces and the paucity of defined water courses result in somewhat different runoff characteristics. In spite of the fact that rain falls infrequently and the surface soil is rarely saturated there are important occasions when local runoff is quite high. Bare, eroded and often rocky surfaces quickly shed surface water to the great benefit of lower "run-on" areas which may receive water equivalent to many times the storm rainfall.

Ancient agricultural practice in the Negev relied very strongly on the utilization of surface runoff as additional soil moisture and elaborate stone mounds and terrace pavements were constructed in order to increase the rate of "run-on" to the lower cultivated areas. There are numerous examples of similar agricultural devices from arid regions of the ancient world and of modern survivals of the tradition.

In the natural environment of the arid zone these "run-on" systems lead to two main benefits or effects. One is the better-quality vegetation which can be supported in these areas of higher soil moisture. In Australia, characteristic longitudinal groupings of native shrubs known as mulga groves flourish along long semi-depressions where they are able to withstand much better the serious droughts which are a feature of the interior. The other benefit obtained from local pooling of runoff is the recharging of aquifers, an essential evaporation-free water supply for stock.

9.4 Modification of solar radiation

Microclimatic conditions at the Earth's surface will be modified by variations in the radiation load. Superimposed on the normal daily and seasonal trends are the changes brought about by surface conditions.

The main influence of the surface on the heat balance occurs through its albedo. Of the common surface materials, water has the lowest albedo with values according to Geiger (1965) of three to ten per cent for sun elevation greater than 40°. Grasses and crops fall in the relatively wide range twelve to thirty per cent whilst trees have somewhat lower values of five to twenty per cent. Soils also exhibit a wide range with seven to ten per cent for dark soils and fifteen to forty per cent for sandy soils.

The albedo may change appreciably with change in moisture content of the surface. For example, for wet sands it changed from nine to eighteen per cent while drying out, and for a particular species of grass it changed from twenty to thirty-two per cent (Geiger, 1965). Albedo of many other plants may be expected to increase on drying. Thus under drought conditions somewhat higher albedos can be expected as surface soils and plants dry out; this would slightly reduce the radiation load imposed on the surface.

Marked changes in surface temperature can be brought about by changes in colour but this fact cannot normally be effectively used in drought amelioration. However, a similar effect can sometimes be achieved by

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mixing unsatisfactory surface soil with better subsoil or the surface can be mulched with straw or other foreign material, e.g. surface stones in some agricultural areas of the Middle East. Increased yields from mulched fields are well proven (Geiger, 1965).

Solar radiation can also be modified by topographic factors, notably by sloping ground. Thus the factors determining the angle of incidence on the surface of radiation are the geographic latitude, declination and altitude of the sun, angle of the slope and the direction it faces. The first three of these are not "adjustable" but careful selection of surface slope and direction can be utilized to advantage. In many locations this is done to gain extra radiation, as in the German vineyards, but the greater transpiration induced in these environments means a greater drought risk in areas subject to water shortage. The effect could possibly be used in reverse, i.e. in areas of normally high radiation load, poleward-facing or other protected slopes would experience lower evapotranspiration demand and therefore lower drought risk.

9.5 Influence of forests on precipitation

When rain falls on a forest some will reach the ground directly through openings in the canopy and the rest is intercepted by leaves and branches from which it may drip to the ground or run down the stems; a certain amount will be retained in the canopy to be either absorbed by the leaves or evaporated. The amount which can be retained in the canopy varies considerably depending mainly on species (Leyton and Rodda, 1970).

Interception loss can be very high when frequent short showers sufficient just to wet the canopy are separated by dry spells during which evaporation takes place. On the other hand, if the same amount of rain fell continuously, interception loss would be relatively small. Evaporation of intercepted rainfall can represent a quite significant loss as it takes place at a rate far higher (up to 4 or 5 times) than transpiration under the same climatic conditions. This accounts in part at least for the commonly observed higher water consumption of forests compared with that of herbaceous cover. On the other hand, stem flow concentrates water around the base of a tree and thus promotes infiltration of water into the deeper soil layers where it is protected from evaporation and may be of appreciable survival value in dry periods.

Whether forests increase the rainfall either locally or elsewhere has long been a controversial subject but it now seems that many of the earlier claims that relatively substantial increases were possible cannot be substantiated by supporting observations. Caution should be exercised in interpreting evidence based on comparisons of rainfall either between adjacent forested and non-forested areas or before and after afforestation or deforestation of a particular area. Generally differences lie within the range of errors of raingauge measurements or can be attributed simply to differences in gauge exposure (Federov and Busova, 1967).

The explanation usually put forward to account for the effect of a forest cover is based on the assumption that forests evaporate more water into the air than lesser vegetation or bare soil (Leyton and Rodda, 1970). However, even if this were the case other conditions for the production of rainfall are not necessarily satisfied, i.e. lifting of the moist air mass to induce cooling and condensation. By the same argument many of the arid areas of the Middle East, South America and Australia should receive more rainfall than they do; water vapour is plentiful but lifting mechanisms are rare.

Other physical effects of the forest which might be considered to increase precipitation are its height, which is an increment to the orographic component, and the roughness factor. On the other hand the convective contribution from surface heating is likely to be very small; in fact glider pilots report general downward movement of air over forests (Leyton and Rodda, 1970). Kitteridge (1948) states that the orographic effect may increase local rainfall by not over three per cent. He also says that the catch of rain in forest clearings is usually greater than in neighbouring open sites by amounts of up to ten per cent but this excess is caused mainly by protection of the gauge from wind in the forest; i.e., it is a rain-gauging error, and when a correction is made for this then rainfall in clearings is estimated to be about one per cent above that in the open.

Thus it may be concluded that even if a forest is capable of influencing the amount of precipitation falling on it, the effect is likely to be quite small compared with rain-gauging errors and of little significance in averting or alleviating drought severity. The effect, even if real, may be reduced even further under conditions of the non-rainfall-productive situation prevailing in a drought period.

9.6 Influence of other evaporation sources on rainfall

The above discussion may be extended to consider the effect of the creation of open water areas on the neighbouring rainfall régime. Claims are often made that such water bodies increase the vapour content of the overlying atmosphere and this situation leads to increased local precipitation.

McDonald (1962) calls this "the evaporation-precipitation fallacy" and quotes a number of examples of claims for increased precipitation made in different parts of the world. McDonald says that in the driest period of any severe drought huge masses of water are still contained in the atmosphere, the principal cause of drought being the lack of dynamic processes capable of producing ascending motions.

Another aspect of the problem concerns the times and distances involved in a water molecule being evaporated, transported through the atmosphere by turbulent processes, condensed and precipitated out again. Since this "turn-over" time is known to be about ten days (Sutcliffe, 1956), it follows from mean wind-speed considerations that the average water molecule must drift many hundreds of miles before precipitation terminates its residence period. That is, the water comprising a given fall of rain or snow has typically originated by evaporation from some oceanic water area lying far upwind of the site of the precipitation.

Thus it may be concluded that proximity to the ocean does not necessarily mean a satisfactory incidence of rainfall. Nor does the establishment of a lake mean any probable increase whatever in the rainfall downwind.

9.7 Modification of evaporation

In addition to the effect of wind shelter, evaporation may be decreased by reducing the net radiation at the surface. In the case of a free water surface, this is not simple and action would be limited to some form of shading. In the case of vegetation, radiation can be changed by shading. Surface albedo can be changed by the application of a chemical. Certain plants have the capability of orientating their leaves relative to the solar beam and thus controlling the amount of radiation received. In particular a number of arid-zone plants are able to reduce the evapotranspiration demand by the latter method. As in the case of water storages, shading of plants would be limited by its cost to special cases.

A completely different approach to evaporation reduction is through the application of chemicals to both water and vegetation surfaces. Suppression of evaporation from water storages has been under investigation for over 20 years, the most successful method being to apply a monomolecular layer to the surface. Most popular chemicals are cetyl alcohol, hexadecanol and octadecanol, usually spread in the form of dust. Mansfield (1967) reports that experiments over several years on storages exceeding 160 hectares in general resulted in savings of 40 per cent or more in winds up to 2 m s^{-1}, of ten to twenty per cent in winds up to 4 m s^{-1} and of virtually zero in winds of 7 m s^{-1}. Overall, the reduction in evaporation was about 15 per cent. Savings in the case of smaller storages were much less.

Another area of interest, particularly because of its great potential, is the application of chemicals to vegetation in order to reduce transpiration. In addition to their use to increase surface reflectivity, chemicals may be used to form surface films to reduce the escape of water vapour or to close stomata, thus increasing the stomatal resistance to vapour transfer. In reducing outward vapour flux, however, closed stomata also limit the CO_2 and O_2 exchange and thus affect plant growth. Select chemicals can partly or completely close stomata with few apparent toxic effects and it has been demonstrated (Slatyer, 1967) that the closure may persist for several weeks; but in the case of plants which produce new foliage immediately after spraying, the treatment may be effective for only a few days. Plant species vary in their sensitivity to chemicals applied to their leaves and test applications are desirable.

The subject of soil treatment by chemicals is of great interest in the U.S.S.R. where studies have been carried out for over 30 years. Soils have been treated with polymers and "surfactants", the objective being to create a 2 cm structural layer on the soil surface with aggregates of about 7 to 0.25 mm in diameter with the following properties: *(a)* it does not decrease the rate of water absorption by the soil; *(b)* it increases the water stability of aggregates; *(c)* it decreases the rate of evaporation of soil moisture by 2 to 3.5 times compared with untreated soil. To produce a 1 cm structural layer, 10-15 kg of polyacryloamid per hectare are required.

Other experiments in the U.S.S.R. have been directed towards the use of latex and its compounds with mineral oils for the surface treatment of soils. Water easily penetrates through this type of surface layer into the soil. Using the cheapest type of latex, which is not toxic, an application rate of 100-150 kg ha^{-1} is sufficient to protect the soil.

9.8 Modification of the rain process by cloud seeding

The influence of artificial seeding of clouds on the rain process is obviously very relevant to the study of drought and has been well covered in a number of papers and texts such as Fletcher (1962), Mason (1962) and Neiburger (1969).

Particular aspects which warrant mention under this heading are the possible changes in the areal distribution of rainfall following seeding and the relative parts played by nuclei of condensation in the seeding of clouds in continental and maritime air mass.

Clouds containing a relatively small number of nuclei may have the same appearance and water content as those which have been copiously supplied with nuclei either naturally or artificially. Because of the big difference in nuclei counts, however, the water in the former is distributed amongst a few large droplets whereas in the over-nucleated cloud the same amount of water goes into a large number of tiny droplets. Such clouds are therefore stable and likely to remain so, without producing rain, for a comparatively long period of time.

The redistribution of areal rainfall may be brought about in two different ways. In one case it may be possible to increase rainfall by seeding over a particular area but, as a result of this operation, a decrease in rainfall may be caused over the area immediately downwind. In the other case, seeding of maritime cloud in a coastal area may produce an over-abundance of nuclei, increase the number of cloud droplets, decrease their average size, and so inhibit the rain process. Possibly then an increase in rain may occur farther inland as compensation for the reduction effected near the coast.

Perhaps the most relevant aspect of nucleation with regard to drought is the behaviour of clouds near the coast compared with clouds over the dry interior of continents. In maritime regions the condensation nuclei count is dominated by a comparatively small number of giant nuclei derived from sea salt whereas in a dusty continental air mass the cloud nuclei population consists of large numbers (10 to 20 times as many) of extremely small nuclei. This results in the same type of stable cloud as by overseeding as discussed above.

Twomey pointed out (in Bowen, 1967) that the condensation nucleus count over the interior was in some circumstances critically dependent on the moisture content of the ground. When this was dry, large numbers of tiny dust particles were released and the cloud nucleus count was correspondingly high. When it was moist, few such particles rose from the ground and the condensation nucleus count was as low as that in a maritime region. Bowen (1967) suggests therefore that simply moistening, as distinct from flooding, the ground in a continental interior is sufficient so to modify the nucleus population that clouds tend toward a maritime type and then rain more easily of their own accord. The same effect may result from the protection to soil provided by full plant cover following good rains even though the surface layer of soil may have dried out.

Artificial means of changing the climate of the arid zone are likely to be unsuccessful unless they induce a change in some features of the general circulation (Gibbs, 1969). For example, even if, as has been proposed from time to time, large lakes were created in Central Australia, as long as subsidence continued over the region the increased evaporation from their surfaces would not be likely to alter the climate significantly.

Cloud seeding is unlikely to effect a major climatic change. The more optimistic estimates of the results of cloud seeding claim a 15 to 20 per cent increase in naturally occurring rainfall. This would not significantly alter aridity. During drought years, in the absence of cloud and of naturally occurring rain, cloud seeding can have no effect.

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APPENDIX I

SUMMARY OF DROUGHT DEFINITIONS

The following summary of drought definitions or associated concepts is based on meteorological, hydrological, soil-water and crop parameters. The definitions have been classified under the following subheadings:

(a) Rainfall

(b) Rainfall with mean temperature

(c) Soil-water and crop parameters

(d) Climatic indices and estimates of evapotranspiration

(e) General definitions and statements

* * *

(a) Rainfall

Author	*Definition of drought or associated concepts*	*Region and comments*
Brounov (early 20th century)	Ten days with rainfall not exceeding 5 mm.	Ref. Tannehill (1947).
Henry (1906)	21 days or more when rainfall is 30 % or less of average for the time and place. Extreme drought when rainfall fails to reach 10 % of normal for 21 days or more.	U.S.A.
Cole (1933)	15 days with no rain.	U.S.A.
Bates (1935)	When annual precipitation is 75 % of normal or when monthly precipitation is 60 % of normal.	U.S.A.
British Rainfall Organisation (1936)	*Absolute drought:* at least 15 consecutive days none of which received as much as 0.25 mm. *Partial drought:* at least 29 days during which mean rainfall does not exceed 0.25 mm per day. *Dry spell:* 15 consecutive days none of which has received as much as 1 mm.	Britain; inapt in normally drier regions.
Hoyt (1936)	Any amount of rainfall less than 85 % of normal.	U.S.A.
Baldwin-Wiseman (1941)	Engineers' drought in Australia is three or more consecutive months with deficit of 50 % from mean rainfall.	Australia.
Blumenstock (1942)	Less than 2.5 mm in 48 hours.	Ref. Thornthwaite (1941)
Conrad (1944)	A period of 20 (or 30) consecutive days or more without 6.4 mm of precipitation in 24 hours during season March to September inclusive.	U.S.A.
Tennessee Valley Authority	When no interval of 21 days received precipitation greater than one-third of normal	Tennessee, U.S.A.
Ramdas (1950)	When actual rainfall for a week is half of normal or less.	India.
Fitzpatrick (1953)	Period terminated by at least 6.4 mm during any 48 hours.	Australia (based on Blumenstock). Evaluated probability that dry spells of any length would occur at any time throughout the year.

(a) Rainfall (contd.)

Author	*Definition of drought or associated concepts*	*Region and comments*
Foley (1957)	Computed residual mass curves of rainfall. Divided values by average annual rainfall to give "index of severity".	Australia. Dividing by annual average makes comparison between stations more reliable. Index is dimensionless.
Gibbs and Maher (1967)	State that rainfall is the best single index of drought and use rainfall deciles to demonstrate temporal and spatial distribution. Areas where rainfall in first decile range roughly coincides with drought areas.	Australia. Provides a useful presentation of areal distribution of drought.

(b) Rainfall with mean temperature

Author	*Definition of drought or associated concepts*	*Region and comments*
Lang (1915)	Precipitation factor $= P/T$ P in mm, T in °C	Germany. Developed to aid climatic classification of soils.
de Martonne (1926)	Index of aridity $I = \frac{P}{t + 10}$ where P is monthly precipitation (mm) and t is mean monthly temperature (°C). Monthly index of I is approximate indicator of aridity.	Used to define climatic limits of deserts, prairies and forests. Does not apply well in cool zones where $t + 10$ approaches zero.
	Index modified to $I = \frac{n \cdot \bar{p}}{t + 10}$ where n is number of days during a certain period from a few days to a year and $\bar{p}$ is daily mean precipitation in the period.	Used extensively by geographers and biologists to compute aridity.
Koloskov (1925)	Ratio of annual precipitation to accumulated mean daily temperature during vegetation period (divided by 100).	U.S.S.R. Ratio may be used as a comparative agroclimatic index.
Selyaninov (1930)	Index given by $k = \frac{\Sigma p}{\Sigma t/10}$ where p is sum of rainfall (mm) during those months when mean temperature is above 10 °C and t is the sum of the daily mean temperatures above 0°C for the same period.	U.S.S.R. Author suggested that a period be considered as a dry spell when $k < 1$ and as a drought when $k < 0.5$.
Köppen (1931)	*Defines "dry" climate by:* $p < 2t$ for regions of winter rain and $p < 2t + 14$ for regions of summer rain or no rainy season where p is annual precipitation in cm and t is mean temperature in °C. *"Desert" climate defined by:* $p < t$ for winter rain; $p < t + 14$ for summer rain; $p < t + 7$ for no rainy season.	Used extensively in classification of the dry climates of the world.
Emberger (1955)	$I = \frac{100p}{(M-m)(M+m)}$ where M is the mean maximum temperature in the hottest month and m is the mean minimum temperature in the coldest month; p in mm and M and m in °C.	France. Based on de Martonne's index, $(M-m)$ is an index of continentality.

(b) Rainfall with mean temperature (contd.)

Author	*Definition of drought or associated concepts*	*Region and comments*
Knochenbauer (1937)	Daily maximum temperatures and humidity at time of afternoon observation used to define a dry spell.	Germany.
Condra (1944)	Period of strong wind, low precipitation, high temperature and usually low relative humidity.	U.S.A. This anticipates the combination of low precipitation and high evapotranspiration.
Henin and Ternisien (1944)	Computed evapotranspiration and drainage from temperature and precipitation.	France. Procedure improved by Turc (1954) incorporating additional factors.
Popov (1948)	Index of aridity $P = \frac{\Sigma g}{2.4\,(t-t')r}$ where P is index of aridity; Σg is annual amount of effective precipitation; $t-t'$ is annual mean wet-bulb depression °C; r is factor depending on day length; and g is that part of precipitation which is available for plants.	
Thornthwaite (1931)	Precipitation effectiveness as a function of mean temperature. $P/E = 1.65\left(\frac{P}{T+12.2}\right)^{(10/9)}$ in mm and °C where P/E is the precipitation evaporation ratio, P is monthly precipitation in mm, and T is monthly mean temperature in °C.	U.S.A. See also under "Climatic indices and estimates of evapotranspiration". Table 1 *(d)*.
Gaussen (1954)	When total monthly precipitation in mm is less than twice the mean temperature in °C.	An approximation to rainfall less than evapotranspiration based on Köppen.
Budyko (1970)	Hydrothermal coefficient $K = \frac{r}{0.18\Sigma\theta}$ *where* $0.18\Sigma\theta$ gives the potential evapotranspiration in mm, $\Sigma\theta$ being the annual sum of daily mean temperatures higher than 10°C; r is annual precipitation in mm.	U.S.S.R.

(c) Soil-water and crop parameters

Author	*Definition of drought or associated concepts*	*Region and comments*
Russell (1896)	A period of months or years during which little rain falls; "the country gets burnt up, grass and water disappear, crops become worthless and sheep and cattle die."	Australia. Author points out that the word drought is not used in Australia in the same sense as in England and elsewhere.
Bova (1941)	Used a drought index K $K = \dfrac{10(H+Q)}{\Sigma t}$ where H is productive soil moisture in mm in the top 100 cm of soil at beginning of spring; Q is precipitation in mm accumulated daily from beginning of spring; $\Sigma\ t$ is the temperature (°C) sum counted from the day of the passage of mean daily temperature through zero.	U.S.S.R. When $K \leqslant 1.5$ beginning of drought damage to plants is indicated.
Barger and Thom (1949)	Evaluated precipitation climate from productive performance of crops.	U.S.A.
Van Bavel (1953)	Agricultural drought should be defined on the basis of soil-water status and resultant plant behaviour.	U.S.A.
Van Bavel and Verlinden (1956)	A condition in which there is insufficient soil water available to crops.	U.S.A.
Thornthwaite and Maher (1955)	Used the water-balance concept with a variable store of soil water.	U.S.A. Use extended to other continents; some results of doubtful value.
White (1955)	Defined drought with respect to xerophilous species using comments on pasture conditions as guide.	Western N.S.W., Australia. Extrapolation to other areas not reliable.
Foley (1957)	Used reports of conditions of crops and livestock published in official bulletins or newspapers together with rainfall analyses (see also under **(a)**).	Australia. Necessarily rather qualitative but helped to define the significance of rainfall deficiency.

(c) Soil-water and crop parameters (contd.)

Author	*Definition of drought or associated concepts*	*Region and comments*
Alpatev and Ivanova (1958)	Based definition of severity on crop yields as compared with long-term mean yields. Because all yield decreases are not result of drought author suggests that only years when yields decreased by 25 % be classified as drought years.	Variations in yield due to different levels of agronomic practices are still greater than those due to droughts (Kulik, 1958).
Kulik (1958)	Used preceding meteorological conditions, soil characteristics and level of agronomic techniques in the region. Decrease of soil water in tilled layer to 20 mm means beginning of dry period and decrease to 10 mm beginning of drought. Semi-drought: ten days with soil water 20 mm in first 20 cm of soil. Drought: as above with 10 mm of water.	U.S.S.R.
Holmes (1962)	States that in the quantitative evaluation of drought for agricultural purposes, precise and regular soil-water observations are most essential.	Canada.
Fitzpatrick (1965)	Developed a water-use model with range of available soil moisture 0 - 10 cm and evapotranspiration losses (E_t) computed from Australia sunken evaporimeter (E_A). $E_t = 0.8E_A$ when soil moisture > 64 mm; $E_t = 0.4E_A$ when soil moisture $\leqslant 64$ mm.	Australia. Has been used in climatic studies and land-use surveys.
Palmer (1965)	A water-balance model which involves rainfall, a coefficient of evapotranspiration, runoff and available soil water.	U.S.A. Method based on the Thornthwaite concept of potential evapotranspiration. See Chapter 3.
Rickard (1966)	Agricultural drought exists when the soil water in the root zone is at or below the permanent wilting percentage. The condition continues until rain falls in excess of daily evapotranspiration.	New Zealand. Drought relief would not occur with say one day of excess rainfall, e.g. 2.5 – 5 mm.
Palmer (1968)	Severity of agricultural drought is defined in terms of the magnitude of the computed abnormal evapotranspiration deficit and expressed as a crop moisture index.	U.S.A. Inputs are weekly values of temperatures and rainfall. A by-product of the 1965 drought work. Theoretically of universal applicability.

(d) Climatic indices and estimates of evapotranspiration

Author	*Definition of drought or associated concepts*	*Region and comments*
Vysotskii (1905)	Established P/E ratios where P is precipitation and E is potential evaporation (both annual values in mm). $P/E = 1\frac{1}{3}$ for moist forest; $= 1$ for transitory forested steppe; $= \frac{2}{3}$ for moderately dry steppe; $= \frac{1}{3}$ for southern dry steppe.	U.S.S.R.
Ivanov (1948)	Indices of $K = P/E$ where P is annual precipitation in mm and E is annual evapotranspiration in mm derived from $E = 0.0018\ (25 + t)^2\ (100 - a)$; t is mean monthly temperature in °C; a is mean monthly relative humidity. Critical values of K for regions of insignificant moisture, deserts 0.00-0.12 Scanty moisture, semi-deserts 0.13-0.29 Insufficient moisture, steppes 0.30-0.59 Moderate moisture, forested steppes 0.60-0.99 Sufficient moisture 1.00-1.49 Excess moisture 1.50	U.S.S.R.
Thornthwaite (1931)	Precipitation effectiveness index based on mean temperature gives water requirement for optimum growth. Water-balance model gives estimate of soil-moisture status.	Originally U.S.A. Use since extended to other continents. Reliability depends on climate and method of doubtful value in many areas.
Penman (1948) (1961) Ferguson (1952)	Estimates water loss from free surface from solar radiation (or sunshine), temperature, humidity and wind, evapotranspiration obtained by using seasonal conversion factor. $E_t = fE$.	Originally U. K. then Europe. Use now extended to other continents with fair to good results. Of little value in dry areas where water supply to plants limited.
Trumble (1937) Hounam (1948) Prescott (1949)	Waite index: $K = 0.38\ P/E^{0.7}$ where P is monthly or annual rainfall or irrigation in mm; E is monthly or annual evaporation from Australian sunken pan in mm. The index $K = 0.54$ was derived from a study of young sunflower plants and extrapolated to field crops and has been successfully used in defining	Australia.

(d) Climatic indices and estimates of evapotranspiration (contd.)

Author	*Definition of drought or associated concepts*	*Region and comments*
Trumble (1937) Hounam (1948) Prescott (1949) *(contd.)*	climatic boundaries for land use and for frequency of periods of non-effective rainfall. This is an improvement on the original Transeau (P/E) ratio which has been applied in some form or another in many countries. To start and maintain growth $K \geqslant 0.54$. For nil drainage through drain gauges $K \leqslant 0.74$. For balance between rainfall and potential evapotranspiration in catchments $K = 1.20$. For balance between rainfall and evapotranspiration in field vegetation $1.30 \leqslant K \leqslant 1.50$.	Australia *(contd.)*.
Turc (1954)	$E = \dfrac{P}{[0.9 + (P/L)^2]^{0.5}}$ mm/annum where P is annual precipitation (mm); $L = 300 + 25T + 0.05T^3$ T is mean air temperature (°C).	France.
Turc (1955)	For short periods $E = \dfrac{P + a + V}{\left[1 + \left(\dfrac{P+a}{L} + \dfrac{V}{2L}\right)^2\right]^{0.5}}$ where E is evaporation in mm in 10-day period; P is precipitation in mm in 10-day period; a is estimated evaporation (10-day) from bare soil; V (a crop factor) = $25\,(MC/Z)^{0.5}$. 100 M is final yield of dry matter (kg/ha). 10 Z is length of growing season (days); C is a crop factor; L is evaporation capacity by the air from $L = (T + 2)\ \dfrac{i^{0.5}}{16}$ where T is mean air temp. °C (in 10-day period) and i is incoming radiation (cal cm^{-2} day^{-1}).	
Baier and Robertson (1966)	Versatile budget (VB) for estimating daily AE from changes in soil moisture per zone $AE_i = \dfrac{k \cdot S'_{(i-1)}\, Z \cdot PE_i}{S} \exp(-w(PE_i - PE))$ integrated over soil zones 1 to n where AE_i is actual evapotranspiration for day i (mm); k is coefficient accounting for soil and plant characteristics in zone;	Canada. See also section 4.2.5. Satisfactory estimates obtained for growing season.

(d) Climatic indices and estimates of evapotranspiration (contd.)

Author	*Definition of drought or associated concepts*	*Region and comments*
Baier and Robertson (1966) *(contd.)*	$S'_{i\text{-}1}$ is available water capacity in zone at end of day i-1 (mm); S is available water capacity in zone (mm); Z is adjustment factor for different types of soil drying curves; PE_i is potential evapotranspiration (mm) for day i; w is adjustment factor for effects of varying PE rates on AE/PE ratio; $\overline{PE}$ is average PE for month or season. exp means exponent.	
McIlroy (1968)	Introduced variables to cover leaf wetness and improved aerodynamic functions.	Australia. Used for conditions of limited soil moisture but measurement of parameters restricts wide application.
Sly (1970)	Climatic moisture index $I = \dfrac{P}{P + SM + IR} \times 100$ where P is growing season precipitation; SM is soil water available to crops at beginning of growing season; IR is calculated growing season irrigation requirement.	Canada. Average seasonal values, indicating differences in water balance, used for soil-climate classification purposes.

(e) General definitions and statements

Author	*Definition of drought or associated concepts*	*Region and comments*
Thornthwaite (1947)	Cannot be defined as shortage in rainfall alone.	U.S.A.
Deacon, Priestley, Swinbank (1958)	Urged the systematization of definitions of drought in relation to effectiveness of rainfall in different climates.	Australia.
Huschke (1959)	A period of abnormally dry weather sufficiently prolonged for lack of water to cause serious hydrological imbalance (i.e. crop damage, water supply shortage).	
Linsley, Kohler and Paulhis (1959)	A sustained period of time without significant rainfall.	U.S.A. The problem is to define "sustained" and "significant".
Subrahmanyam (1967)	To the meteorologist drought is a rainless situation for an extended period during which some precipitation should normally have been received depending on location and season. The agriculturalist considers drought as a shortage of moisture for his crop. The hydrologist views it as being responsible for depression of surface and underground water levels or diminution of streamflow. To the economist drought means a water shortage adversely affecting the established economy of the region. Water shortage is basic to drought; it is a relative rather than an absolute condition.	Inadequate in areas of seasonally low rainfall and in moist areas of high transpiration.

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APPENDIX II

DROUGHT AND THE NEED FOR A WORLD CLIMATIC WATCH

1. Application of a possible world climatic watch on drought

Drought may be studied from many aspects but the following are particularly relevant from the meteorological viewpoint:

(a) Historical study of drought;

(b) Real-time assessment of the status of drought (surveillance);

(c) Drought prediction.

Generally speaking, historical drought studies should be the responsibility of NMCs* but on occasions when the phenomenon is widespread, covering more than one country, co-operation between Members may be necessary. RMCs* may not generally be adequately equipped to provide all the data required for these studies and it may be necessary to rely on direct co-operation between Members. Historical drought studies may take two main forms: one is the areal study of particular droughts with or without a defined boundary; the other is the temporal study of drought at a point. The latter is of course strictly of NMC concern.

Areal studies of drought should be the more important because they normally involve detailed synoptic studies for a specific period and thus may lead to insight into the reasons for drought, a conclusion most unlikely from the study of temporal pattern at a point. Thus RMCs could provide valuable information on analysed synoptic charts at both surface and upper levels. For hemispherical circulation studies the assistance of the relevant WMC would be required.

The real-time assessment of drought would require a broad-scale observing and reporting network which certainly should involve NMCs and, over many parts of the world where multi-national continental drought is involved, would require the assistance of the data-collecting facilities of RMCs. The aid of WMCs should be invoked on special occasions. The real-time monitoring and assessment of drought would involve the collection of rainfall and "related" drought data. Initially, meteorological data from the WWW synoptic networks might suffice for this purpose. However, as experience is gained in this type of analysis it may be necessary to supplement the synoptic network data with information on evaporation, radiation and soil water. Drought parameters or indices would be computed by the centre and RMCs might also be used in the dissemination of advice to other regional Members.

The third study area of drought concerns its prediction, and this field, as will be appreciated by all meteorologists, would involve intensive research and real-time commitments. Considering first research, as the necessary preamble to any real-time experimentation, it would be desirable to investigate both statistical and synoptic aspects of drought incidence. Statistical procedures would necessitate long-term records of rainfall and related drought parameters and the most proficient procedure for such studies would be to utilize the facilities of the NMC with international co-operation as necessary. RMCs will not normally be organized to store historical climatological records for all Members. On the other hand, where synoptic studies are being undertaken, RMCs should be able to provide chart sequences, at least for the recent years of the World Weather Watch era.

**Note:* The World Weather Watch (WWW) provides the following types of centre: WMCs = World Meteorological Centres; RMCs = Regional Meteorological Centres; NMCs = National Meteorological Centres.

Having conducted appropriate research leading to the development of a drought-prediction service, the RMCs then should be in a position to provide operational facilities for real-time activities. Procedures to be followed in real-time drought operations would be the forecasting of the continuation or cessation of drought.

2. Relevant drought data

In the very early days of meteorological reporting, when IMO was the international co-ordinating body, it was universally agreed that standardization of data format was necessary. This was particularly important in regard to the meteorological elements observed and the way in which data were encoded for international exchange. In more recent years WMO has crystallized and consolidated these aspects of data exchange and, in addition, has gone a long way towards the complete standardization of instrumentation used to make these observations. Thus a meteorologist working in one country should be well informed on the availability of relevant data in neighbouring countries, or, in fact, anywhere in his region of the world.

The prime source of data for both real-time and research studies is the synoptic network. This provides data from a well-spaced network of stations at fixed specified times. These data are used by NMCs, RMCs, and WMCs where they are available on synoptic charts and in many instances in archival magnetic tape storage. Monthly summaries are forwarded by observers to NMCs, RMCs and WMCs, usually at the end of each month, where they are processed in considerable detail and form the basis of routine climatological publications. These data are retained permanently in archives from which they are readily available for national and international research purposes.

In addition to the national synoptic network most countries operate secondary climatological and agrometeorological networks comprising stations which do not telegraph coded messages to the NMC. The observations are often directed towards a specific purpose, such as agriculture or hydrometeorology, but summaries of observations are, as in the case of synoptic stations, returned each month to the national data archives and are readily available to potential users. In some instances these stations may be vitally important in drought studies as would be an agrometeorological station observing soil water, evapotranspiration and crop growth in addition to the standard meteorological observations.

Surface meteorological observations may be made manually and entered into field books or they may be derived from automatic instrumentation in the form of either analogue traces, punched paper tape or magnetic tape. In these unprocessed forms, data would be available almost exclusively in NMCs.

Data in field books should be available for climatological and research purposes almost immediately after the close of the month either directly from such books, in the form of summaries or from punched cards or tapes.

Data from long-term remote recorders are generally available only at intervals, depending on the time period of the equipment or the frequency of visitations to remote sites. Except in special cases where automatic transmission facilities are incorporated in equipment design, data from these remote recorders are available for research purposes only.

Of the various meteorological elements of concern in drought studies only rainfall, temperature, humidity, cloudiness, and wind are included in synoptic reports. Accumulated precipitation amount at a point would be one of the most essential elements in a real-time drought-surveillance service. At the present time precipitation amount is not mandatory in the synoptic code. Furthermore, synoptic reports from a few stations are missing from time to time due to unavoidable circumstances. Missing reports become more frequent during storms because of communication difficulties just at a time when precipitation may be heaviest and the report most necessary. Some provision should be made in the synoptic code to report the accumulated precipitation, say from 1 January rather than the total amount which falls between observations. This would ensure that the total precipitation would reach the various meteorological centres even though the information might be late. If reports are received regularly it would be little trouble to calculate the precipitation amount for any short period such as between synoptic times.

The amount of rainfall data collected at present and stored at WMCs and RMCs would be inadequate for a proper study of drought and research workers would need to obtain from NMCs data for the many minor or intermediate rainfall stations necessary for such a study. For temporal studies of drought it would be necessary to have long-term consistent records of rainfall and related elements and the prime source for these for many years to come will be NMCs. In fact, it is unlikely that WMCs will ever be able to specialize in the collection and processing of long-term climatological records for their whole region of responsibility.

Without doubt the most spectacular observing tool in the last decade is the meteorological satellite and enough significant pictures have been collected to appreciate both real-time and research value. In relation to drought their greatest application will be in the prediction field. Other useful information deducible from satellite pictures is the location of the snow-line, which has value in the planning and assessment of water resources.

In more recent years an Earth resources satellite has been introduced for research purposes. Sensors used on these satellites include scanners in the infra-red and visual wavelengths. It has already been demonstrated that satellites operating in these wavebands are able to sense certain changes in surface characteristics. For example, it may be possible to identify the outbreak of potato blight or the state of "wetness" of a vegetated surface. In addition to surface wetness, good progress is being made in the identification of underground water located close to the surface. This information is already finding practical application in agriculture and in hydrology. Once the system becomes operational on a real-time basis, assessment of surface wetness will have obvious application in flood forecasting and the data should also be significant in both real-time and research studies of evaporation and drought.

Other related "drought" observations, which are normally not included in synoptic messages, include evapotranspiration, solar and net radiation, river flow and soil water. Evapotranspiration is more complex than most because it is often observed in other forms or may be estimated from other meteorological elements. Furthermore, it is specific for existing crop and soil-water conditions. Radiation is receiving special attention by the Global Atmospheric Research Programme (GARP) and, although there may be some areal restrictions such as in the Tropical Experiment, there is good chance that some data may become operationally available. The river-flow and soil-water observations are of rather limited interest except to agriculturists, hydrologists and specialist meteorologists and, in some countries, are the responsibility of the national hydrological authority or agricultural ministry rather than the NMC. The World Weather Watch is likely to improve the availability of these data through co-operation in data cataloguing with specific national hydrological and agricultural authorities likely to hold them.

3. **Quality control of data**

As a result of human or instrumental errors or faults in the telecommunication system there is an ever present likelihood that errors will exist in synoptic observations received by NMCs, RMCs and WMCs.

Errors may be detected by computer or manual processing on a real-time basis depending on the degree of sophistication of chart preparation. To reduce the workload on the higher status centres it is hoped that all errors of this nature would be isolated and corrected by the NMCs if time permits. However, should errors undetected by NMCs be isolated by the RMC or WMC system it will be necessary for these centres to alert the particular NMC to the fault. Where errors result from transmission faults NMCs will approach telecommunication authorities for corrective action.

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NMCs have the responsibility of maintaining the highest possible observational standards and this may be achieved through adequate observer training, regular inspections of stations for observer liaison, checks on station exposure and instrument maintenance.

NMCs will also be in a position to effect essential data control through examination of monthly observations in field books and the application of standard statistical tests designed to detect random and consistent errors. This particular operation is probably the most effective method of maintaining quality control of data.

If these procedures are adequately and routinely performed there is a high probability that data collected and processed for World Weather Watch purposes will meet the high standard required for research purposes but it is anticipated that it will be some years before a uniformly high standard is reached throughout the world.

4. Processing of data

The three WMCs (Melbourne, Washington and Moscow) are each equipped with modern large-memory computers capable of reading punch-cards and paper and magnetic tape.

Surface and upper-air synoptic data from national and international networks are received by the computers where they are quality-controlled and, as required, processed according to a number of numerical models. Graphical attachments permit the machine production of charts such as mean sea-level isobaric and upper pressure-level contours and prognostics.

It is hoped that one of the most valuable accomplishments of the World Weather Watch will be the production of medium-period weather forecasts (5-30 days) based on the latest available numerical models. Outstanding success cannot be expected initially but with the development and completion of research experiments such as GARP there is considerable hope of incremental improvements in techniques. In particular these forecasts will be of great significance in drought situations and even a moderate improvement in accuracy would have a tremendous bearing on the planning of agricultural activities and related decisions.

In addition to real-time products, the computer complex at WMCs and RMCs will also hold a large body of processed data in store. This can be drawn upon in future drought studies such as the production of significant synoptic charts relative to a drought situation or seasonal anomalies in specific meteorological elements.

Finally synoptic observations should be retrievable from these computer centres to provide point climatological records according to the period of data held in store.

5. Networks for drought studies

The World Weather Watch plan calls for key synoptic stations spaced at about 500 km and making eight observations per day at each station. However, the area over which such a station network is representative is relatively small and a network of such density may not be sufficient for drought surveillance. Many very significant droughts are confined to relatively small areas and for intensive studies of these situations stations should be separated by no more than 100 km. However, they need not all be synoptic stations by World Weather Watch definition, e.g. two observations per day would suffice in most situations and it would not be necessary for all additional stations to report on the NMC telecommunication system.

World Weather Watch network plans do not recommend raingauge spacing as this is irrelevant in the synoptic context. Experience indicates, however, that drought studies require gauges spaced at between 20 and 50 km, depending on local topography and the detail of the study. Because of the variability of rainfall it is possible for an individual raingauge to record unrepresentative rainfall; and the more dense the network, the less chance that anomalous observations will lead to unrepresentative conclusions.

Networks for real-time studies such as assessment of a current drought situation need not be as dense as those for research purposes.

Field reports on the drought, as it affects various crops, water supplies, etc., are also desirable.

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