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The water resource in tropical Africa and its exploitation

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INTERNATIONAL LIVESTOCK CENTRE FOR AFRICA
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ABSTRACT

This report gives an insight, for non-specialists in the field, into the wide range of problems concerning water development in tropical Africa. It deals with the mechanics of the hydrological cycle, the origins of the wide variations in rainfall, the potential for water resources development in pastoral areas and low-cost methods of exploiting these resources. Problems of water quality are also covered in outline. The final chapter makes recommendations, principally covering planning and operation and maintenance. Reference is made to recent advances in the field of water resources with examples taken mainly from anglophone countries in Africa.

KEY WORDS

/Tropical Africa//pastoral hydraulic engineering//water resources//water management//hydrology/ /water quality//precipitation/–/surface water//runoff//ground water//water conservation//evapotranspiration//water erosion//water balance/

RESUME

Ce rapport vise à familiariser les non-spécialistes avec la large gamme des problèmes que connaît l'Afrique tropical en matière de mise en valeur de ses ressources en eau. Il traite du mécanisme du cycle hydrologique, des origines des variations importantes dans la pluviométrie, du potentiel qui existe dans les régions d'élevage pour le développement des ressources en eau et des méthodes d'exploitation peu onéreuses. Les problèmes concernant la qualité de l'eau y sont également ébauchés. Dans le dernier chapitre, des recommandations sont faites principalement dans le domaine de la planification, de l'exploitation et de l'entretien. Les récents progrès accomplis en matière de mise en valeur des ressources en eau y sont évoqués et illustrés par des exemples tirés principalement de l'expérience de pays africains anglophones.

MOTS-CLES

/Afrique tropicale//hydraulique pastorale//ressources en eau//aménagement hydraulique//hydrologie/ /qualité de l'eau//précipitation/–/eau de surface//ruissellement//eau souterraine//conservation de l'eau/ /évapo-transpiration//érosion hydrique//bilan hydrique/

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PREFACE

Livestock development projects initiated in sub-Saharan Africa over the past two decades have absorbed close to one billion American dollars worth of aid. Much of this aid, particularly during the period 1961 to 1975, has been directed towards the semi-arid and arid zones where the provision of drinking water for man and his livestock has been the largest single item of expenditure. In these zones, which are occupied primarily by pastoral people, shortages of drinking water occur every dry season, of which there are one or two a year depending on the region. Therefore any form of water development might be expected to improve the living standards of pastoral people in normal years and their chances of survival in times of drought.

Unfortunately this is often not so. Water development may contribute to imbalances in the use of land and water resources in dry areas. These imbalances are exacerbated and intensified when they coincide with detrimental climatic fluctuations, both wet and dry, making the effects of drought and flood more severe and leaving a legacy of erosion and desertification. Recent improvements in international communications have given extensive publicity to natural disasters and helped to focus world attention on the problems of water and livestock.

The most recent example of such a catastrophe in Africa was the drought in the Sahel from 1968 to 1973. It caused the collapse of the livestock industry of five countries – Chad, Mali, Mauritania, Niger and Upper Volta – and severely damaged that of two others, Senegal and the Gambia.

It was against this background that ILCA was prompted to put together a series of state-of-knowledge reports on water and livestock problems in Africa. There were a number of scientific disciplines involved, and the subject has been divided into three topics, each of which is dealt with in a separate research report (RR) as follows:

RR 6. *The water resource in tropical Africa and its exploitation,*

RR 7. *Livestock water needs in pastoral Africa in relation to climate and forage,*

RR 8. *Organisation and management of water supplies in tropical Africa.*

The three reports are best read in relation to one another.

As well as providing technical guidelines for national planning authorities, these reports review the interrelation of animal metabolism, water, climate and forage. They also consider the complexities of human organisation and management upon which the success or failure of the most carefully prepared and executed water development project will largely depend. The authors are primarily addressing senior personnel engaged in scientific research, planning and implementation. The justification for this approach is that if there were simple solutions to the problems of water and livestock in Africa, they would have been found some time ago.

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1. INTRODUCTION

This report deals with the water resource and its exploitation from an engineering point of view, but is aimed at an essentially non-engineering audience. Any state-of-the-art report is bound to be incomplete and, in this case, the sins of omission have to be weighed against the inclusion of material, based on practical experience, of the kind which cannot be found in textbooks.

This report is, therefore, a personal perspective of the authors, who have had to be selective in covering a very wide field in a very small volume. It has been necessary to concentrate, as far as possible, on principles, giving details only in order to enable the reader to pursue a particular topic through the references cited in the text. One of the major aims of the report has been to give an insight, for non-specialists in this field, into the wide range of problems in water development and to provide general guidelines for future planning.

The report begins with a description of the major controls on the climatic environment. The variation of rainfall in time and space is presented as the central problem of water development. It attempts to explain why there is often too little rainfall or too much, and why the situation changes from year to year, with the greatest variability occurring in the areas of greatest need. It highlights the problems of predicting this variability and of describing it in a way which can be used for planning purposes.

Chapter 3 deals with what happens to rainfall after it reaches the ground. It describes the various components of the hydrological cycle and how they are interrelated. There is also a brief discussion of how the components can be measured or estimated and how the hydrological cycle can be affected by man's activities.

Chapter 4 considers the potential water resources of the pastoral areas of tropical Africa. The various types of water resource are classified as a prelude to discussing the means of exploitation in Chapter 6.

Chapter 5 is a brief introduction to the problems of water quality. This is frequently a constraint on water development activities and it is therefore appropriate to emphasise water quality considerations as a prelude to exploitation.

Chapter 6 covers a very wide field, of necessity in a general and skeletal manner. The means of exploitation of a water resource are site specific, and the range of options depends as much on economic considerations as on technical feasibility. An attempt has been made to introduce the important concepts of appropriate technology and community participation. Emphasis has been placed on low-cost systems, on the assumption that more elaborate and sophisticated projects are dealt with in detailed feasibility studies by professional water engineers and scientists, who are able to present and evaluate the full range of options for a particular project.

The final chapter deals with some aspects of planning which are related specifically to the evaluation of water resources. Two vital aspects – operation and maintenance – are also discussed, to emphasise the need for simple and reliable water supply systems. These should involve the local communities, as far as possible, in every stage of planning, implementation and operation.

In conclusion, some recommendations are made on key areas which play an important role in the successful implementation and continued operation of schemes for water supply. A plea is made for the diversion of some funds into practically orientated research, if only to keep pace with the need for new solutions to problems in the development of water resources in the face of rapidly increasing populations.

It is often said that the amount of rainfall is not the problem; it is the distribution of that rainfall, in space and time, which forms the basis of the dilemma for planners. It is of no help to subsistence pastoralists to know that nearby humid areas have plentiful water if the costs of distributing that water far outweigh the economic returns. It is technically feasible to pump water from lakes and distribute it by pipelines to almost any pastoral area. Saline water can be desalinated and rivers impounded to provide supplementary water supplies. These methods, however, are extremely high-cost solutions to the problem and cannot be justified by even the most generous cost-benefit analysis.

Low-cost solutions have to be sought for the foreseeable future, until energy costs form a much smaller proportion of the operating costs of water supply schemes. In the meantime, the arid and semi-arid pastoral regions of tropical Africa will be faced with making the best use of their available water resources. This precludes the large-scale transfer of water from the wetter regions or from large perennial rivers. It implies that the exploitation of water resources must be based on three maxims:

- conservation
- optimum utilisation
- efficient management.

The first of these, conservation, implies not only the storage from wet season to dry season of whatever rain falls, but also the retention of that rainfall on the surface to allow maximum infiltration. To this end, it necessitates soil conservation and the arresting of vegetational degradation caused by overgrazing, burning or deforestation. The point is made in Chapter 6 that investment in water supply schemes will largely be futile without the management of river catchments or areas of groundwater recharge. The corollary is that investment in soil and water conservation makes sound economic sense, in view of the high cost of providing water supplies, rectifying damage to roads and hydraulic structures, and removing sediment from irrigation channels.

Optimum utilisation involves knowing what the options for the exploitation of water resources are, and selecting the 'best' option in terms of a specific criterion. This criterion needs not necessarily be that of low cost where the social benefits are unquantifiable. It is difficult to assess the benefits of improved health and of the increase in time available for other occupations which arise from the provision of safe and adequate water supplies. It is suggested that planning of water supplies is best accomplished within a complete drainage basin or region. What might appear the best option at project level may not be the best one in the context of national planning or of large multipurpose schemes. Adequate surveys are an essential prerequisite for optimum utilisation. For such surveys, a quantitative knowledge of the components of the hydrological cycle is required, together with the predictive tools to assess what is feasible for the future.

Efficient management requires no explanation other than to emphasise that it includes the establishment of efficient operation and maintenance procedures. Wherever possible, these procedures should be based on the expertise of local communities, with a minimum of reliance on outside assistance. Imparting a sense of ownership of the water supply scheme to the local community is essential to its long-term operation.

No attempt has been made to give cost indicators for the various options proposed, except in relative terms. It was thought that giving examples of cost would be of little relevance to future projects. Costs are critically sensitive to the location of project areas, both in terms of access to sites and in relation to the prevailing technological capacity of the country in question.

Another consideration is that many countries are busily engaged in developing low-cost technologies to enable them to move towards the target of providing safe drinking water within easy reach of rural populations. These activities have been stimulated by the United Nations 'International Drinking Water Supply and Sanitation (IDWSS) Decade' (1980-1990). Dramatic reductions in per caput cost have already been reported from Malawi (UNDP/Malawi Government, 1982) in relation to new low-cost boreholes and dug wells. A recent seminar on low-cost groundwater development for rural communities, held in Malawi in December 1982, also indicated that similar cost reductions are being achieved in Sudan, Benin, Upper Volta and Togo.

While the value of the United Nations 'decade' activities in focusing attention on the plight of the developing countries must be acknowledged, it is clear that this drive has been initiated during the worst possible period for obtaining the necessary funds to achieve its designated targets. The world economic recession, and an increasing detachment by traditional donor agencies from their commitment to developing countries, has meant that funds are available for only a fraction of the proposed activities. At the same time, the World Bank estimates that there are 1.2 billion rural people (excluding those in China) who still lack access to safe water (World Bank, 1982). The same report shows that out of the total investments by the International Development Association of US$ 6610 million between 1961 and 1982, less than 4% was on water supply. It is encouraging to note, however, that two thirds of that 4% have been invested since 1978 – a reflection of the World Bank's increasing focus on water and sanitation.

Concentrating on human populations does not divert funds away from providing water for livestock. On the contrary, the spin-off from the IDWSS decade is likely to be very beneficial to the livestock populations and their owners. There are indications that investment in the water sector in African countries may double, but this will be due to a redirection of funds into water and sanitation projects rather than an increased total commitment from donors (World Water, 1982). If this is the case, every effort should be made to increase the cost effectiveness and success rate of water projects. In this way water development can assist in increasing the survival rate of livestock in drought years, in raising the standard of living of pastoralists, and in improving the quality of life of those people living in the arid and semiarid areas of tropical Africa.

2. CLIMATE AND RAINFALL

2.1 THE TROPICAL ATMOSPHERE

Tropical Africa can be defined geographically as the area of the continent lying between the Tropics of Cancer and Capricorn, or, meteorologically, as the area of Africa where the weather sequences and climate differ distinctly from those in middle and high latitudes (Lockwood, 1972).

In this zone, the effects of the spinning earth are least marked and, with the exception of the east coast, widespread uniformity of temperature and humidity gives the nearest approach to the classical model of the general circulation of the atmosphere, the Hadley cell.

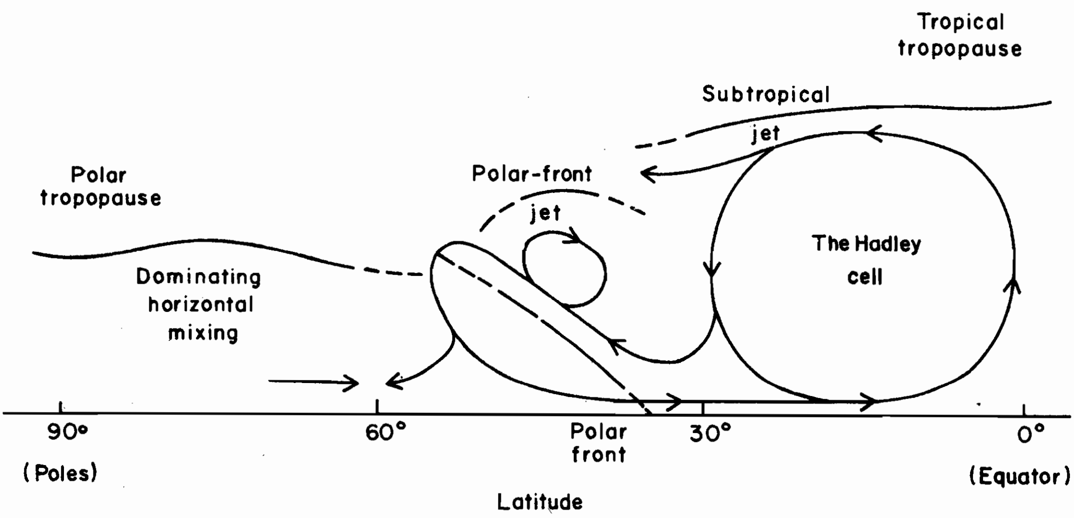
This model is shown schematically in Figure 1. In the simplest terms, one can consider the atmosphere as a gigantic heat engine, driven by solar radiation, and modified by the earth's rotation. Solar radiation provides the energy source for evaporation and for heating the earth's surface.

The equatorial regions receive more incoming radiation than they lose through longwave radiation. This surfeit of net radiation at the equator is balanced by a radiation deficit towards the poles. The temperature gradient which builds up between equator and poles drives the general circulation of the atmosphere and, in the absence of rotation, would lead to a poleward flow of warm air in the upper troposphere and a compensating return flow towards the equator at surface levels.

Because of the earth's rotation, a discontinuity in the poleward flow exists around latitudes 30°S and 30°N. Here the increasing effect of the earth's rotation produces a belt of high wind speeds directed towards the west, known as jet streams. These increases in wind speed in the upper levels of the atmosphere place a limit on the upper poleward flows.

To add further to the complexity of the picture, waves exist in the upper atmosphere in

Figure 1. *Diagrammatic representation of the Hadley cell and meridional circulation.*



Source: Lockwood (1972).

middle latitudes. These are associated with the boundary between polar and tropical air. An eastwards flowing jet stream is a feature of these waves; occasionally this stream is displaced to the lower latitudes. This displacement is particularly pronounced when the sun is overhead in either the northern or southern tropics.

Satellite studies have revealed, however, a much more complex pattern of atmospheric circulation over land areas within the tropics than the above comments suggest (Barrett, 1974). Theoretical studies have also demonstrated that more complex patterns of equatorial cells can exist (Asnani, 1968).

Nevertheless, the simple model is useful in explaining the existence of the major deserts. Subsidence of air from the Hadley cell rotation in subtropical regions makes it almost impossible for clouds to form, and thus for the rain-making process to be initiated. The Sahara and Kalahari deserts, therefore, are the result of atmospheric subsidence and are not due to a lack of atmospheric moisture.

The simple model also explains the existence of the trade winds. These are prevailing winds flowing from the subtropical anticyclones towards the equator. The southeast and northeast trade winds flow towards the zone of relatively low pressure in the region of the equator. According to Findlater (1971) two troughs exist, often separated by a westerly counterflow. This counterflow can be an important feature in bringing moist maritime air to the western side of the continent.

Although the stream of relatively cool maritime air associated with the trade winds is capable of bringing rain, the flow is often divergent, and the presence of a trade wind inversion suppresses any convectional growth. The altitude of the inversion rises towards the equator as the broad-scale subsidence weakens, and the equatorial zone becomes a zone of convergence where towering cumulous clouds can develop.

This zone is often termed the 'intertropical convergence zone' (ITCZ), and the migration north and south of the equatorial troughs associated with the ITCZ, following the apparent movement of the sun, is one of the most important climatic factors in Africa. The ITCZ is not a zone of rainfall. It is a zone of instability within which a number of factors can lead to a triggering of the rainfall mechanism. Often the zone is difficult to identify, or it may be split into a series of zones within the equatorial troughs. Because of the relatively uniform pressure and temperature, small pressure gradients often modify the flow pattern on the surface of continents in the equatorial regions. The interaction between the flows and topographic barriers (such as the highlands of East Africa) and large lakes (such as those in the Great Rift Valley) gives rise to local forced convection and to heavy rainfall.

The release of latent heat by condensing water vapour may trigger a series of violent thunderstorms over a wide area, even though the build-up of the critically unstable layer may take several days. Much of the rainfall in the tropical regions is of this type. Recent satellite imagery has confirmed the presence of cloud clusters – concentrations of cumulous clouds in linear arrays or in irregular clusters, separated by clear areas of weak subsidence. Unfortunately, the origin and mechanism of such features, which were formerly much more difficult to observe let alone study, is still not fully understood. Thus, in a region where the onset and duration of rainfall is critical to man, prediction and forecasting of rainfall are still in their infancy.

2.2 REGIONAL CLIMATOLOGY

Our understanding of the dynamic atmosphere within the tropics is imperfect. However, the movements of the equatorial troughs is an important and significant feature which helps to identify the area within which rainfall is most likely to occur. The controls on the movement of the troughs are partly extratropical and arise from the energy exchange between the equator and the poles. Clearly, the strength and position of the subtropical high-pressure systems are critical and determining how far north and south of the equator the equatorial troughs move.

The devastating droughts in the Sahel region of West Africa during 1972 can be explained in terms of anomalous easterly flow patterns over western Arabia and Africa between the equator and 20°N (Krueger and Winston, 1975). This easterly flow inhibited the growth of the normal westerly flow and has been shown by Minja (1982) to have arisen from anticyclones centred over North Africa and Egypt. Mean flow patterns show that anticyclones are usually confined to the North African coast and are very much weaker than those which occurred in 1972. This example is given to show that an understanding of dynamic climatology assists in explaining much of the deviation from the statistical means on which most regional climatological studies are based.

Many subjective attempts have been made to classify regional climates e.g. Herbertson (1905), Koppen and Geiger (1954), Pollock (1968) and

Griffiths (1972). All suffer from trying to portray a dynamic system in a static sense. More recent works acknowledge this difficulty and attempt to describe the mechanisms or controls on the seasonal changes in pressure, temperature, rainfall and wind patterns (Lockwood, 1972).

There is still a need, however, to present the mean patterns, and the arithmetic mean values of meteorological variables are the climatic indices most readily available. Climatic classifications based on such statistics, although useful for broad comparisons, may produce a misleading picture of 'fluid continuum subject to kaleidoscopic variations in its form' (Barrett, 1974).

For example, the mean annual rainfall, at a particular station, is expected to be equalled or exceeded 50% of the time. Rainfall is expected also to be less than or equal to the mean for the other 50% of the time. For both agriculturalists and pastoralists the risk factor in accepting mean annual rainfall as a design parameter is too high, and far more appropriate indices are the rainfall amounts with an 80 or 90% probability of occurrence. These can be found from an analysis of the frequency distribution of annual rainfall. They are values which, on average, will not be reached in 1 year out of 5 (80%), or 1 year out of 10 (90%).

Mean annual or mean monthly rainfalls, however, are valuable statistics in their own right, often being strongly correlated with other variables. Their presentation below is perfectly justified as long as the limitations of arithmetic means are fully understood.

Acknowledging that classifications of climate based solely on mean statistics are of limited value to the user, it becomes apparent that the purpose to which a classification is to be put becomes the most important criterion in any 'genetic' classification. In terms of water resources, precipitation is the most important climatic variable, and it is well known that its temporal and spatial variability will determine the range of human activities which are possible in practice. In seeking to evaluate both this range of activities within certain areas and the constraints or factors limiting these activities, it is useful therefore as a starting point to take the mean patterns of seasonal rainfall over tropical Africa. These patterns are closely related to the mean positions of the equatorial troughs, and anomalies in rainfall distribution can frequently be related to significant changes in the position of the troughs in particular years.

Thompson (1965) gives mean monthly rainfall patterns in a series of 12 maps of which four are reproduced here (Figures 2 to 5). These demonstrate clearly how the equatorial troughs migrate north and south bringing rainfall to different parts of Africa.

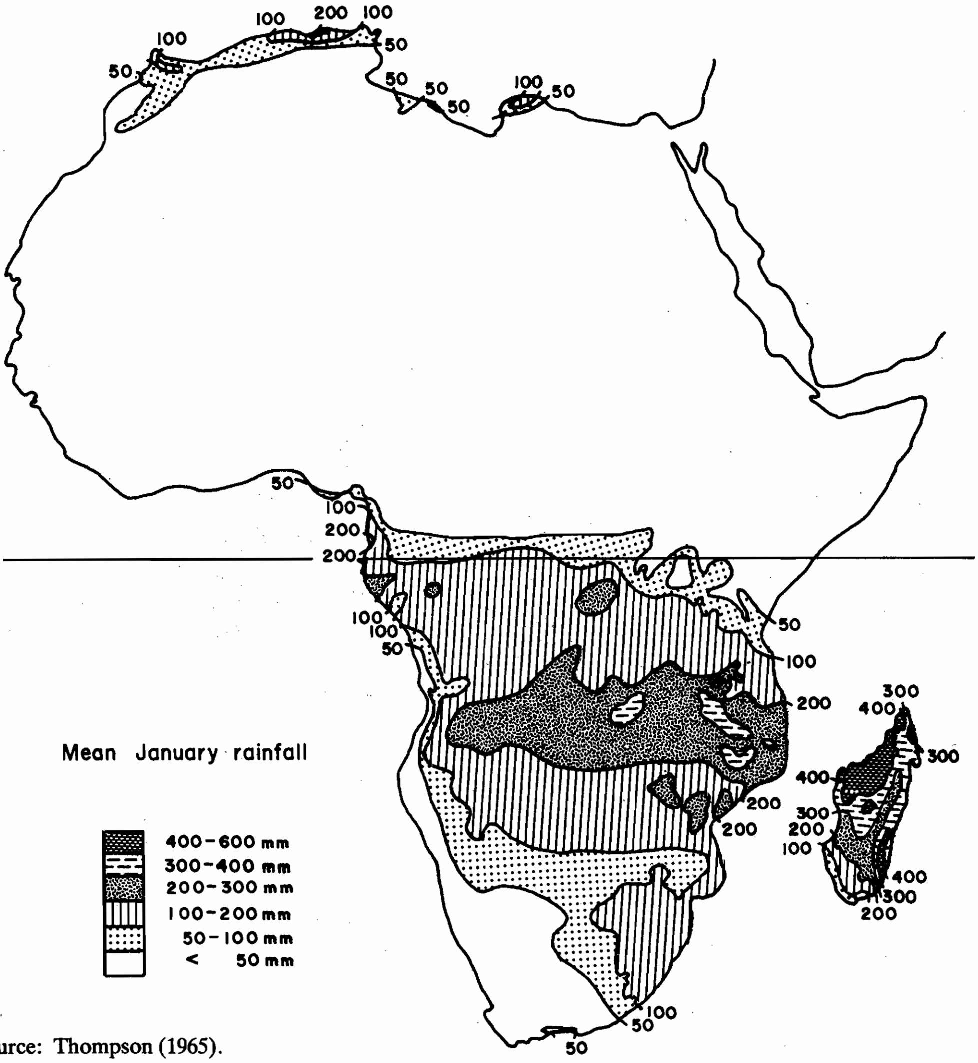
In January (Figure 2), the main areas of precipitation are in a zone centred between latitudes 10°S and 15°S, with maxima on the eastern side of the continent. This pattern corresponds well with the penetration south of the equator of the northeast monsoon in the Indian Ocean (Findlater, 1971), bringing the heaviest rainfall to Madagascar and the eastern continental margins. It is also during January when tropical cyclones develop in the southern Indian Ocean bringing, on average, two storms of hurricane intensity a year. The steep topography of the island of Madagascar helps to promote some of the most intense and heavy falls of rain (Barrett, 1974). Occasionally, these storms penetrate the Zambezi Valley and Mozambique and Malawi. Generally speaking, however, the frequency of tropical storms in this part of the Indian Ocean is very small compared to an average of 22 per year in the northwest Pacific Ocean, and about 10 per year in the northeast Pacific Ocean.

The dryness of the western side of the continent south of the equator is usually attributed to the dominance and persistence of the south Atlantic anticyclone, which gives rise to strong subsidence in the layers near the surface (Thompson, 1965).

By April (Figure 3), the troughs have moved far enough north to produce a zone of maximum rainfall astride the equator. Flow from the south Atlantic anticyclone towards troughs situated significantly further to the north in West Africa (between 10° and 15°N), brings rainfall to the West African coast as far south as Angola. In East Africa, the northeasterly flow across the northern Indian Ocean has been replaced by a strengthening southeasterly flow which penetrates as far inland as the East African highlands, bringing rainfall to a wide area. Strong flow develops first at low levels, then at higher levels, and a notable feature is the bifurcation of the core of the southern monsoon. One branch penetrates eastern Africa, while the other recurves between two well marked equatorial troughs into a westerly flow towards the southern tip of Sri Lanka.

As the troughs continue to move northwards, the circulating flow becomes most marked in July (Figure 4). During this month, the northern equatorial trough is positioned along the south Arabian peninsula, whereas the southern equatorial trough is astride the equator. The core

Figure 2. *Mean January rainfall in Africa.*

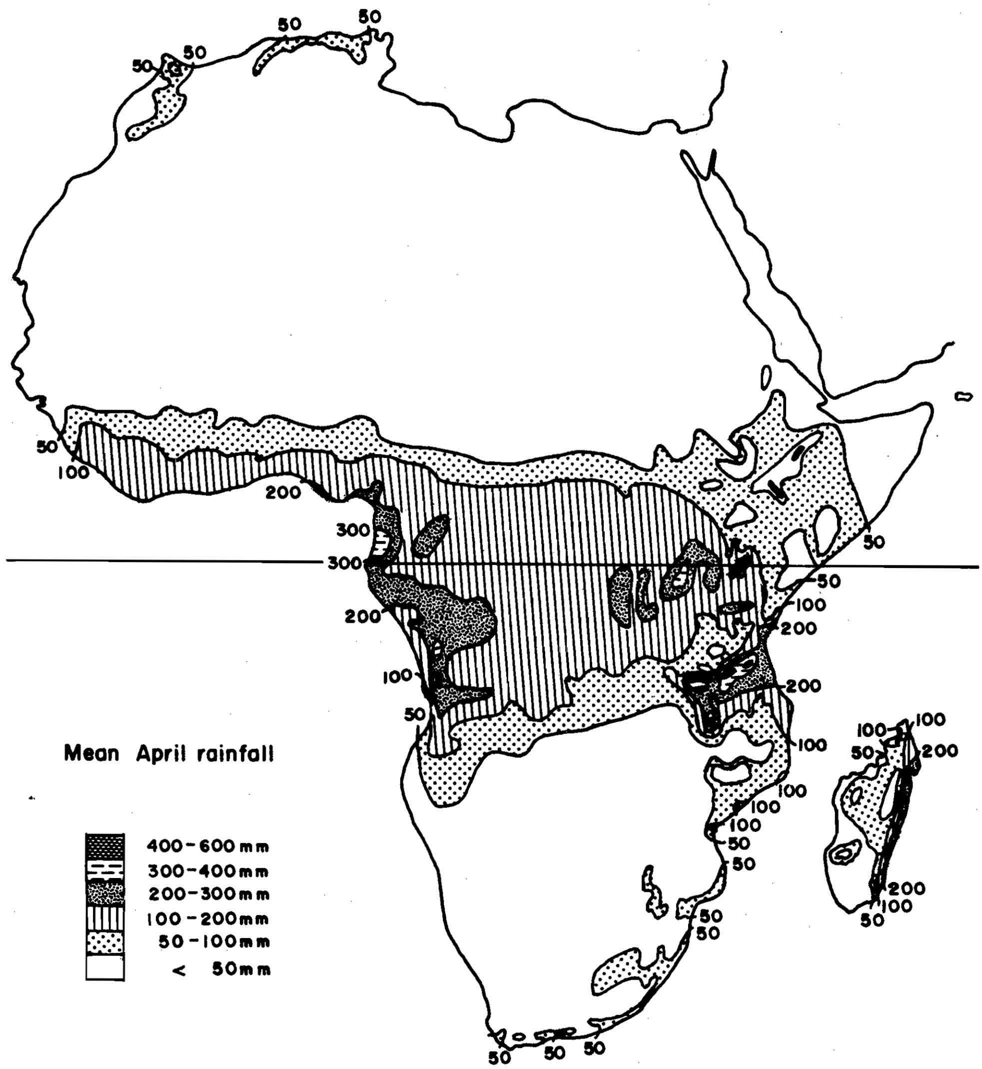


Source: Thompson (1965).

of highest wind speeds at the surface now runs from the northern tip of Madagascar in a northwesterly direction, turning north across the equator just off the East African coast, and curving northeastwards across the Indian Ocean, to become the well known southwest monsoon of the Indian subcontinent. As can be seen from Figure 4, only a very small area of the east coast receives rainfall, together with the eastern margins of Madagascar. In West Africa, however, the southwesterly flow between the two troughs has strengthened, producing the 'southwest monsoon' (Lambergeon, 1982), and bringing rainfall, in a zone between 0° and 10°N, across the continent as far east as Ethiopia.

In the months between July and September, the situation changes little except for a gradual movement south of the southern equatorial trough in West Africa. By October (Figure 5), the weakening of the subtropical pressure system over southern Africa allows a southward extension of the convergence in central Africa. In East Africa, the northern equatorial trough moves over Ethiopia and Somalia and, once again, the westward penetration of the southeasterly monsoon current brings rainfall to coastal regions. Rainfall is also found in the southeastern part of the continent as a weak flow of the southeasterly monsoon swings south of Madagascar. This pattern intensifies with the penetration of the north-

Figure 3. *Mean April rainfall in Africa.*



Source: Thompson (1965).

east monsoon south of the equator in November and December, until the January stage is reached again with strong convergence south of the equator on the eastern side of the continent, bringing widespread rainfall.

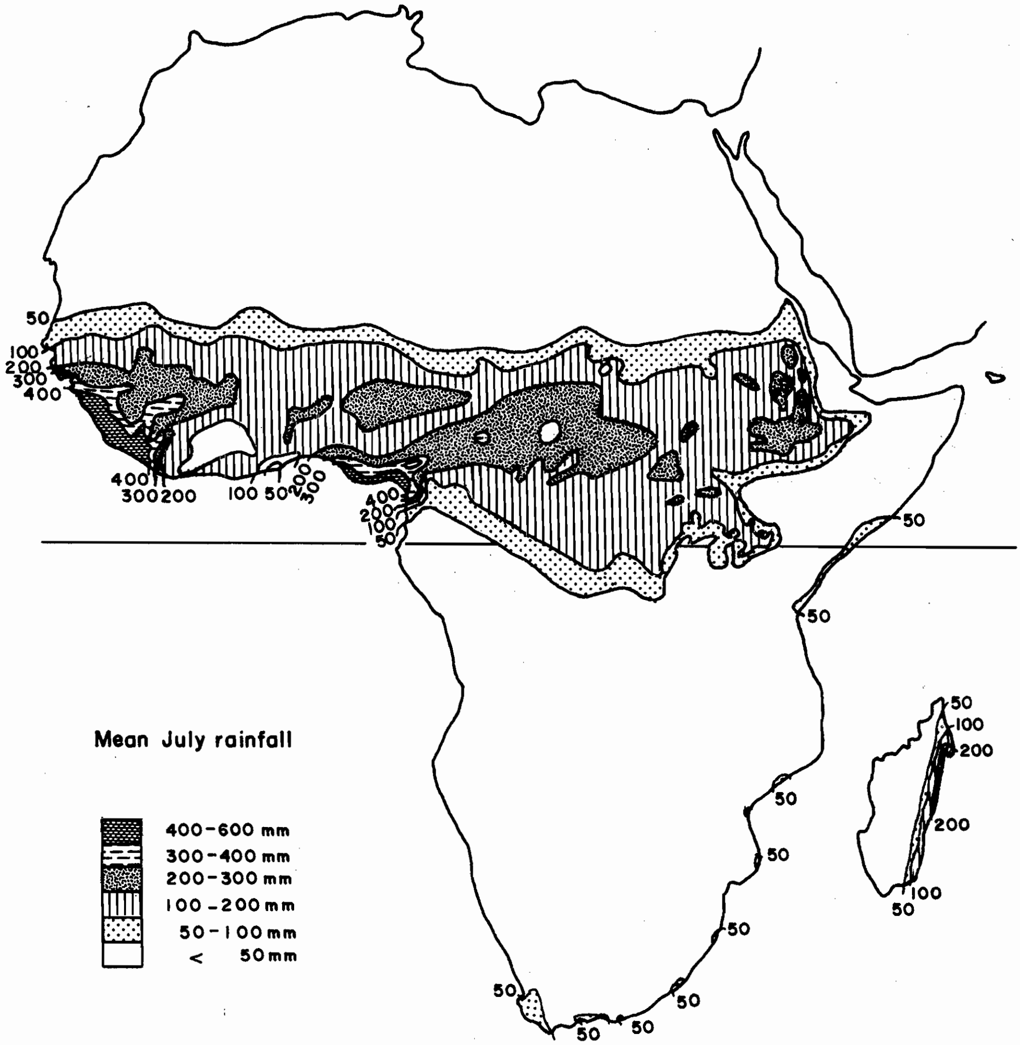
These illustrations of the seasonal movements of mean monthly rainfall are subject to the comments made previously about variability and reliability. Individual annual and seasonal distributions of rainfall can, and do, vary widely from the mean pattern. In addition local conditions, particularly in the vicinity of mountains, escarpments and large bodies of water, can produce deviations from the general picture.

An example of the reliability of rainfall within the overall seasonal pattern is shown in Figure 6, which gives the 4:1 confidence limits of peak date and seasonal quantity of rainfall for African stations between 8°N and 5°S (Manning, 1956). The relationship between peak rainfall and the apparent movement of the ITCZ is clear.

The seasonal and annual ranges of temperature, humidity and potential evaporation are much less pronounced, except that these variables exhibit strong and regular diurnal variations. From the point of view of water resources, potential evaporation is particularly important since it integrates the effects of all other variables including rainfall.

As progress is made towards an understanding of the mechanism and controls of the general circulation of the atmosphere, so the reliability of

Figure 4. *Mean July rainfall in Africa.*



Source: Thompson (1965).

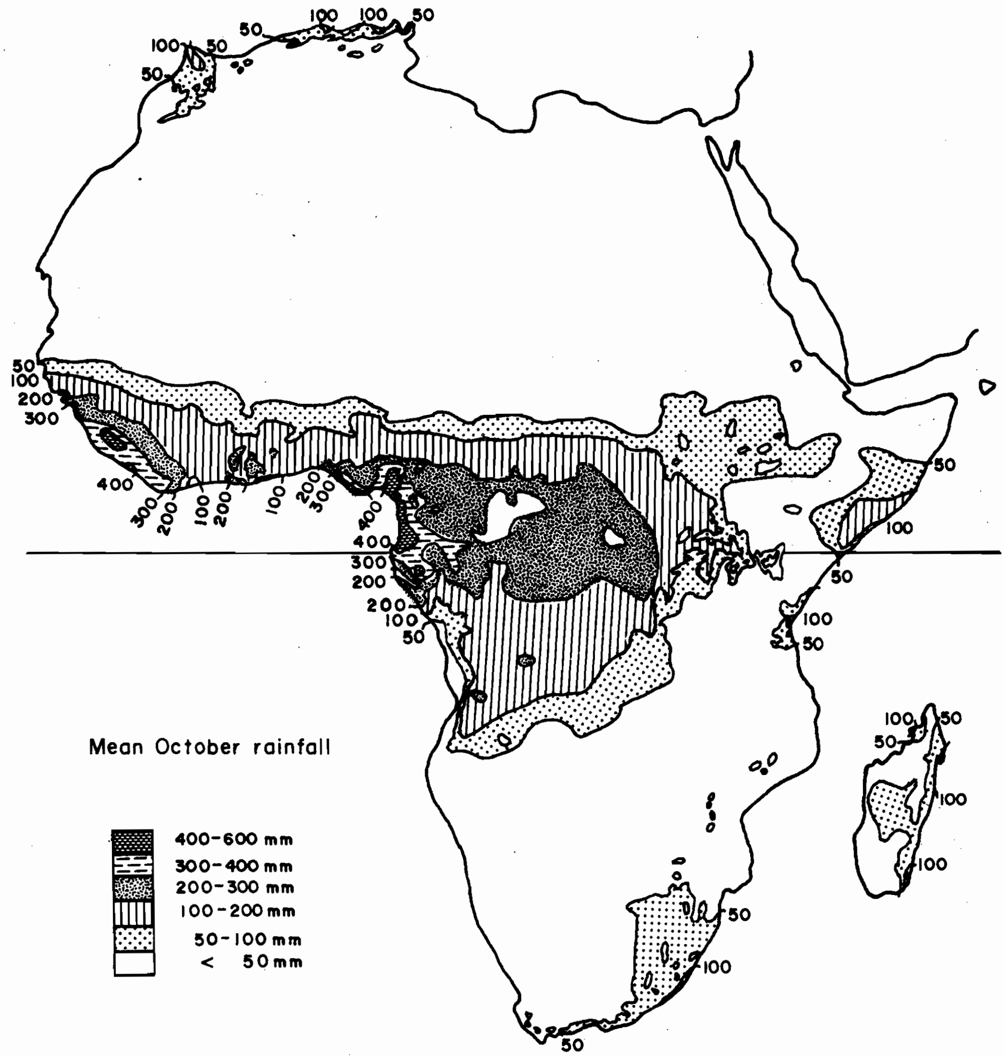
forecasts will increase. At the present time, however, it is not possible to forecast either the onset or the duration and intensity of tropical rainfall. However, it is possible to obtain reliable predictions of rainfall amounts where sufficient data exist for a statistical analysis of a series of events. This will indicate the average likelihood of an event occurring over a specified period. But it will not indicate when the event will occur, nor does it assist in predicting, for example, when there will be a series of dry years such as those which have characterised many of the major drought periods. This topic is dealt with in a later section.

2.3 MEASUREMENT OF POINT RAINFALL

Rainfall is most commonly measured daily at a fixed time in the morning, and the measured quantity, expressed as depth in millimetres, is attributed to the previous day. The 'standard' rain gauge varies in orifice diameter and height above the ground in different countries, but most have adopted the World Meteorological Organisation guidelines of a 150 to 200 cm^2 collector area positioned 30 cm to 1 m above the ground. If rainfall occurs during the morning, and a rain gauge is read during a storm, the total quantity in that storm will be attributed to two separate days. This is an important factor to take into account when assessing the frequency of large falls of rain.

Another type of rain gauge is the recording, or autographic, gauge which traces amount of rainfall against time on a strip chart. Some newer gauges employ tipping buckets which record, via

Figure 5. *Mean October rainfall in Africa.*



Source: Thompson (1965).

a magnetic switch, counts or tips in a digital form, on either solid-state or magnetic-tape loggers. These rain gauges are used to analyse the intensity of rainfall and are particularly useful in assessing storm profiles, infiltration rates, surface runoff or rainfall erosivity.

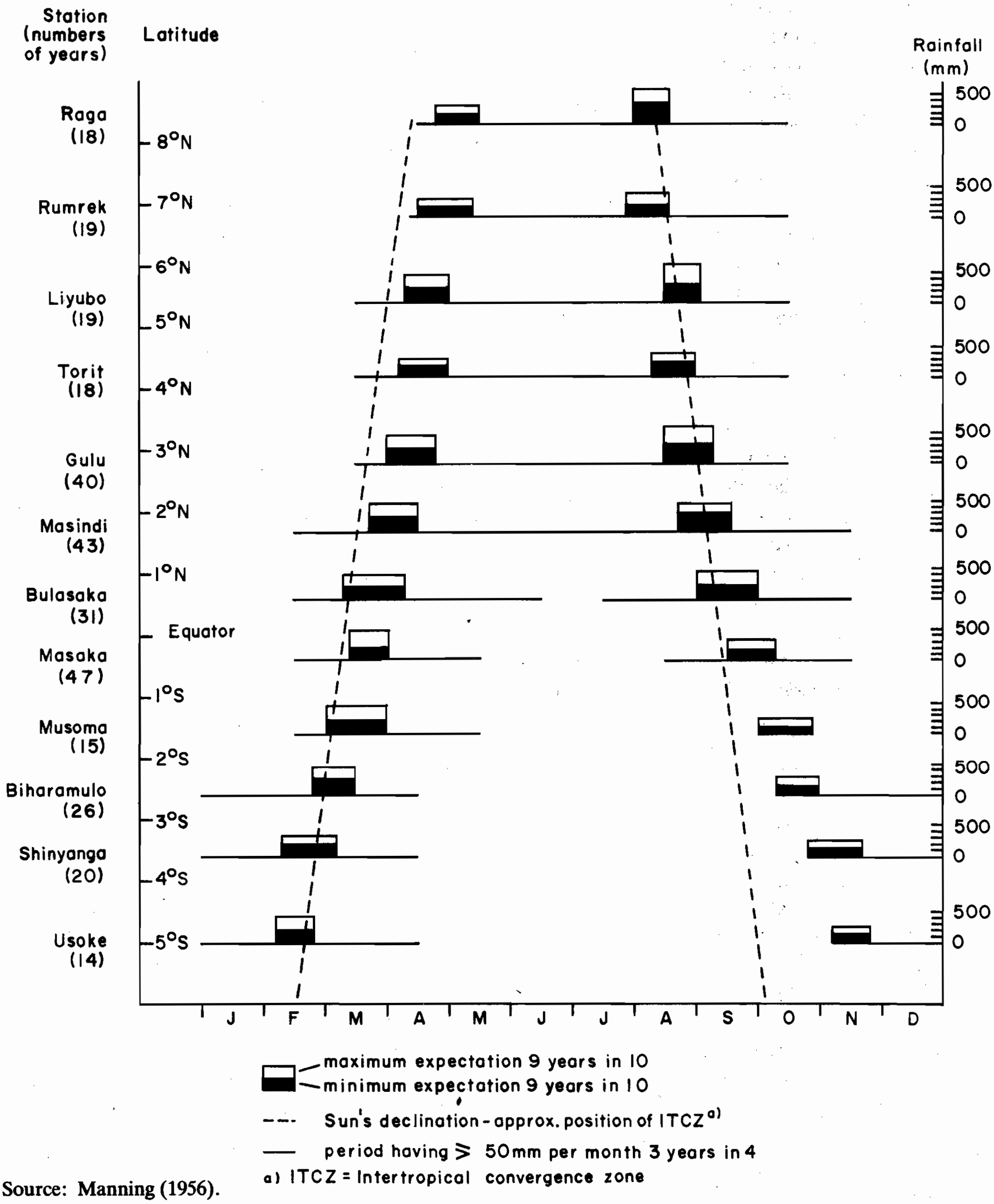
Storage gauges are rain gauges which are left in remote areas for periods of time between visits ranging from 1 week to 1 month. Where evaporation is high, oil can be used to inhibit losses. Calibrated dipsticks are used to measure rainfall between visits. Once again, small solid-state recorders make it possible for storage gauges to be measured at infrequent intervals to give daily rainfalls. The usefulness of all rain gauges is limited by the effectiveness of protection against vandalism.

Radar has been used with some success to measure rainfall in cases where high costs can be justified in order to obtain real time data, as in the case of flood forecasting. Radar has also been used to detect hail formation in the tea-growing area of Kericho in Kenya. Clouds can be seeded to curtail the growth of large hailstones, which can cause costly damage to a high-value cash crop.

With the ever increasing quality of satellite imagery it is possible to correlate cloud type, density and thickness with rainfall, using 'ground truth' stations. Once again the cost of such a computer-based exercise has to be weighed against the value of the rainfall data.

Telemetering of rainfall information has been developed in certain remote areas to minim-

Figure 6. *4:1 confidence limits of peak date and seasonal quantity of rainfall for latitudes 8°N to 5°S.*



Source: Manning (1956).

ise the transport costs of gathering rainfall data. This, and other remote or automated techniques (including the use of automatic weather stations), is not likely to replace the widespread system of volunteer observers using simple standard rain gauges until realistic monetary values can be placed on sets of reliable rainfall data. However, as technological advances reduce capital installation costs, and as fuel prices continue to rise, the gap between manual and automated systems in terms of total costs may not be so great.

2.4 ESTIMATION OF AREAL RAINFALL

Rainfall over an area is usually estimated from a network of rain gauges. In theory, these gauges should either be placed in a random sampling array, or be set out in a regular or systematic pattern. A combination of sampling techniques, as in a stratified random sampling network, is often used to increase the efficiency of sampling i.e. to decrease the number of gauges required to estimate the mean rainfall with a given precision (McCulloch, 1965).

In practice, gauges are usually placed near roads and permanent settlements for convenience of access, rather than according to a strict sampling array. There is a danger that bias can be introduced into the estimated mean areal rainfall. This was first pointed out by Thiessen (1911), who advocated the construction of Thiessen polygons to give a weighting inversely proportional to the density of rain gauges.

In mountainous areas, for example, fewer gauges tend to be placed in the inaccessible areas which often have the highest rainfall. Careful inspection is needed, therefore, to determine whether the mean is affected by serious bias, and whether this can be corrected using the Thiessen method.

The most rational way of estimating mean rainfall is by constructing isohyets (lines joining places of equal rainfall) on a map of the area in question. This takes into account such factors as the increase in rainfall with altitude on the windward side of hills and mountains, the rain shadow on the leeward side of hills and mountains and the aspect of topographic barriers in relation to prevailing winds. The assumption is made that rainfall is a continuous spatial variable i.e. if two rain gauges record 100 mm and 50 mm respectively, there must be some place between the two gauges which has received 75 mm. Glasspoole (1915) sets out some criteria for drawing isohyets for the British Isles which have general application.

Once the isohyets have been drawn, mean areal rainfall is calculated by computing the incremental volumes between each pair of isohyets, adding the incremental amounts and dividing by the total area.

Because of the labour involved in measuring the area between isohyets, several automated techniques have been devised. These include fitting various 'surfaces' to the rainfall data, calculating Thiessen polygon areas automatically or applying finite element techniques (Edwards, 1972; Shaw and Lynn, 1972; Lee et al, 1974; Chidley and Keys, 1970; Hutchinson and Walley, 1972). These techniques are basically designed to accommodate irregularly spaced rain gauges in areas where spatial variation is important, or to provide techniques which can readily be adapted to the computer processing of rainfall data.

In semi-arid areas, the temporal and spatial variability of rainfall is such that rainfall networks are rarely dense enough to reflect adequately either the mean or the variance of areal rainfall. Even where relatively dense networks (e.g. 1 gauge per 700 km^2) are installed as part of research programmes (Edwards et al, 1979), there are difficulties in constructing isohyetal maps, and considerable changes in the seasonal pattern of rainfall can be discerned.

Generally speaking, random sampling networks give a better estimate of the variance of mean rainfall, and systematic sampling networks give a better (i.e. unbiased) estimate of the mean. In some cases, as in network design, the former is more important since it leads to estimates of the precision of the mean or, conversely, to determining the number of gauges necessary for estimating the mean with the required precision. For most general purposes, however, a systematic spatial coverage can be relied upon to give unbiased estimates of the mean.

In this context it is useful to distinguish between an estimate's precision i.e. its repeatability in a sampling sense, and its accuracy, which is a function of both the sampling technique and the estimate of 'true' rainfall at a point.

Rain gauges are of many different heights above the ground. Variations in the cross-sectional area of the gauge from its nominal value, which may be due to poor construction or damage, overexposure of gauges to high wind speeds across the orifice, shelter of the gauge by vegetation, and common observer mistakes, all contribute to inaccuracies in point rainfall measurements. Normally these are small compared to the seasonal and annual variability of rainfall but, in certain cases, these potential sources of error have to be taken into account. Such cases include the measurement of rainfall above forest canopies and in areas of high wind speed.

2.5 FREQUENCY DISTRIBUTION OF ANNUAL, MONTHLY AND DAILY RAINFALL

Agriculturalists and pastoralists require statements concerning the reliability of rainfall. A convenient means of making such statements is provided by confidence limits. These are defined as the estimates of the risk of obtaining values for a given statistic that lie outside prescribed limits (Manning, 1956). The limits commonly chosen are 9:1 and 4:1. With 9:1 limits a figure outside the limits is to be expected once in 10 occasions, and half of these occasions (i.e. one in 20) are to be expected below the lower limit and half above the upper limit. Thus the 9:1 lower confidence limit of annual rainfall would represent the level of rainfall which is expected not to be reached 1 year in 20. Similarly, the 4:1 lower confidence limit is expected not to be reached 1 year in 10.

In order to establish values for such limits, it is necessary to assume a theoretical frequency distribution to which the sample record of data can be said to apply. Manning (1956) assumed that the distribution of annual rainfall in Uganda was statistically normal. Jackson (1977) has stressed that annual rainfall distributions are markedly 'skew' in semi-arid areas and the assumption of a normal frequency distribution for such areas is inappropriate. Brooks and Carruthers (1953) make general statements that three-yearly rainfall totals are normally distributed, that annual rainfall is slightly skew, that monthly rainfall is positively skew and leptokurtic, and that daily rainfall is 'J'-shaped, bounded at zero. They go on to suggest that empirical distributions be used, such as log-normal for monthly rainfall, and an exponential curve (or a similar one) fitted to cumulative frequencies for daily rainfall.

For annual rainfall series which exhibit slight skewness and kurtosis, Brooks and Carruthers suggest that adjusting the normal distribution is easier and more appropriate than using the Pearson system of frequency curves (Elderton, 1938; Fisher, 1922). As the degree of skewness and kurtosis increases, log-normal transformations should be used.

These comments apply equally well to tropical rainfall where annual totals exceed certain amounts. For example, Gregory (1969) suggests that normality is a reasonable assumption where the annual rainfall is more than 750 mm. On the other hand, Manning (1956) gives examples where the normal frequency distribution fits reasonably well to stations with less than 750 mm (Table 1). Kenworthy and Glover (1958) suggest that in Kenya normality can be assumed only for wet-season rainfall. Gommes and Houssiau (1982) state that rainfall distribution is markedly skew in most Tanzanian stations.

Inspection of the actual frequency distribution, at given stations, and simple tests for normality can quickly establish whether or not the normal distribution can be used. Such tests include the comparison of the number of events deviating from the mean by one, two or three standard deviations with the theoretical probability integral. If not, a suitable transformation must be chosen before confidence limits or the probabilities of receiving certain amounts of rainfall can be calculated.

Maps have been prepared for some regions, particularly East Africa (East African Meteorological Department, 1961; Gregory, 1969), showing the annual rainfall likely to be equalled or exceeded in 80% of years. These are extremely useful for planning purposes although, as Jackson (1977) points out, these refer to average occurrences over a long period of years. Statements such as 'the rainfall likely to be equalled or exceeded 4 years in 5' must be qualified by 'on average' to indicate that it does not rule out the occurrence of, say, 3 years of 'drought' rainfall in a row.

2.6 FREQUENCY DISTRIBUTION OF EXTREME VALUES

When dealing with the frequency distribution of maxima or minima, it is necessary to use other empirical frequency distributions which give a more satisfactory fit to the observed data. There are no rigid rules governing which type of distribution is most appropriate to a particular case, and a variety of empirical frequency or probability distributions are available in standard statistical textbooks (Table 2). As a general guide, extremal distributions are concerned with the exact form of the 'tail' of the frequency distribution. Because such occurrences are rare events, it is unusual to have a sufficiently long record for the

Table 1. *Confidence limits of rainfall for some stations receiving less than 762 mm.*

Station	Annual mean (mm)	No. of years of record	4:1 limits		Deviation	
			lower	upper	actual	expected
Utusi, Uganda	760	14	406	1118	4	2.8
Sokota, N. Nigeria	693	40	508	864	7	8.0
Namanga, Swaziland	661	35	381	940	6	7.0
Chipinea, Zimbabwe	653	23	406	889	4	4.6
Kibaya, Tanzania	643	12	330	940	2	2.4
Maiduguri, N. Nigeria	627	38	406	864	8	7.6

Source: Manning (1956).

Table 2. *Common types of frequency distribution used for hydrological events.*

Type	Characteristics	Example
1. Binomial	Discrete events in two categories	Number of 'dry' months in each year
2. Poisson	'J'-shaped distribution of discrete events; possible number of occurrences very small	Frequency of heavy rainstorms
3. Normal	Symmetrical, bell-shaped continuous distribution (Gaussian)	Annual rainfall in wet regions
4. Adjusted normal	As for 'normal distribution' but slightly skew	Annual rainfall
5. Log-normal	Positively skew and leptokurtic	Annual rainfall in semi-arid areas, monthly rainfall
6. Pearson type I	Bounded both ends, bell or 'J'-shaped, skew	Monthly rainfall with very dry months
7. Pearson type III	Bounded one end, bell or 'J'-shaped, skew (log-normal is a special case)	Frequencies of wind speed
8. Extreme distribution type I	Asymptotic, unbounded (Gumbel)	Flood frequency, rainfall intensity/frequency
9. Extreme distribution type III	Asymptotic, bounded at a minimum value	Drought frequency

shape of the asymptotic part of the curve to be defined with any certainty. Brooks and Carruthers (1953), for example, feel that the Gumbel distribution (Gumbel, 1942), which is commonly used in flood frequency prediction, tends to underestimate the magnitude of the rarer rainfall events.

In most applications it is usual to linearise the distribution by calculating cumulative frequencies and then plotting on double logarithmic versus linear graph paper (extreme probability graph paper). If the actual distribution is close to the theoretical distribution postulated by Gumbel, the plotted points approximate to a straight line. An example of this is shown in Figure 7 which demonstrates how a cumulative distribution can be linearised by the use of special probability paper (Ven te Chow, 1964). The same author points out that the abscissae and ordinates are normally reversed to show the probabilities as abscissae. Figure 8 is an example of the more usual presentation of data plotted on extreme probability paper. In this case maximum daily rainfalls for June, in Lagos, closely fit the Gumbel distribution.

In this context it is useful to mention that most analyses of frequencies of rainfall or other hydrological events are expressed in terms of the recurrence interval of an event of given magnitude. The average interval of time, within which the magnitude of the event will be equalled or exceeded, is known as the recurrence interval, return period or frequency. It is common, therefore, to refer to the 10-year or the 100-year flood, or the 24-hour rainfall, for example.

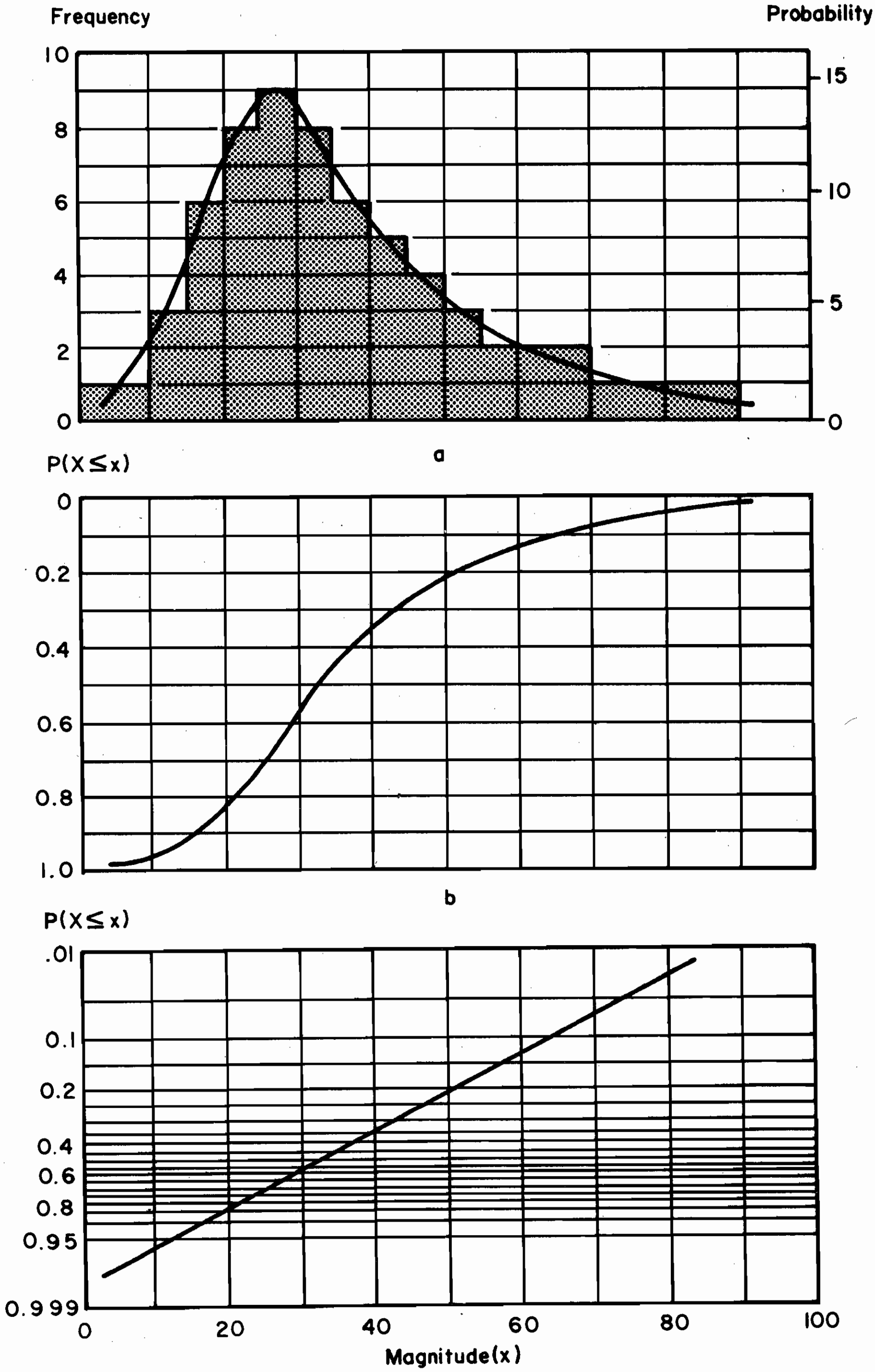
The recurrence interval (N) should not be thought of as the actual time interval between events of similar magnitude. It means that in a long period, say 10 000 years, there will be 10 000/N events equal or greater than the N-year event. It is possible, but not very probable, that these events will occur in consecutive years (Linsley and Franzini, 1964).

2.7 RAINFALL INTENSITY, DURATION AND FREQUENCY

It is a general feature of rainfall, and one which is not necessarily confined to the tropics, that a small proportion of intense storms of short duration produce most of the total rainfall (Richl, 1954; 1956). Thus, 10 to 15% of rain days account for 50% of the rainfall, 25 to 30% of rain days account for 75% of the rainfall, and 50% of days with the smallest rain amounts account for only 10% of the total. In semi-arid areas such as northern Kenya, this pattern is even more marked as depicted in Figure 9, which shows that almost half the rainfall events over a 2-year period contributed less than 2% of the total rainfall, and that they had rainfall intensities of less than 5 mm/h. On the other hand, 6% of the storms fell with intensities greater than 25 mm/h (a threshold value above which rainfall may be considered erosive, according to Hudson, 1971), and these storms contributed over 70% of the total rainfall (Edwards et al, 1979).

Most of the record falls of rain are associated with intense tropical cyclones. Figure 10 shows the world's highest recorded rainfall. The totals

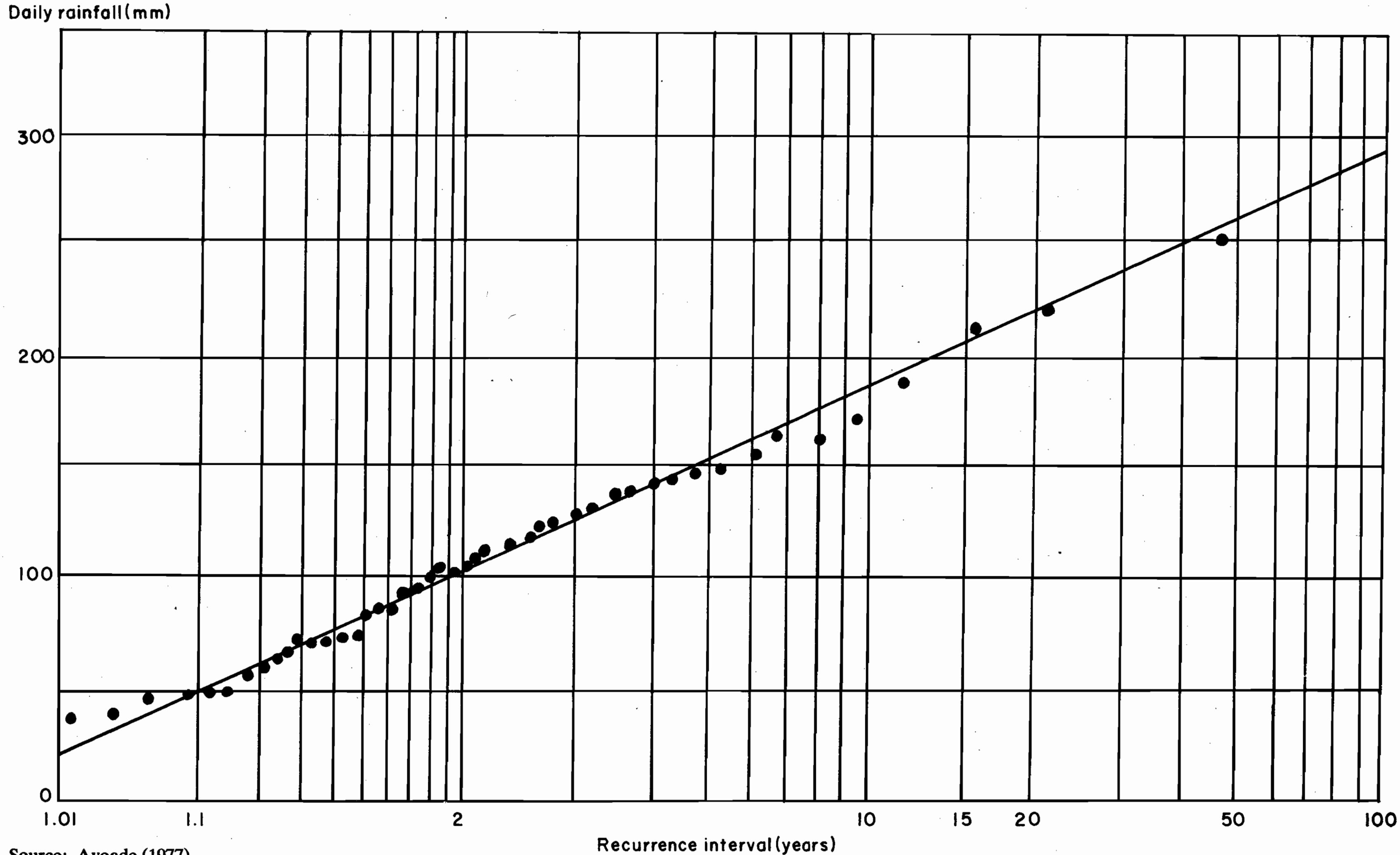
Figure 7. *Linearisation of a statistical distribution.*



a. Frequency or probability distribution curves.
b. Cumulative probability curve plotted on rectangular coordinates.
c. Cumulative probability curve linearized on probability paper.

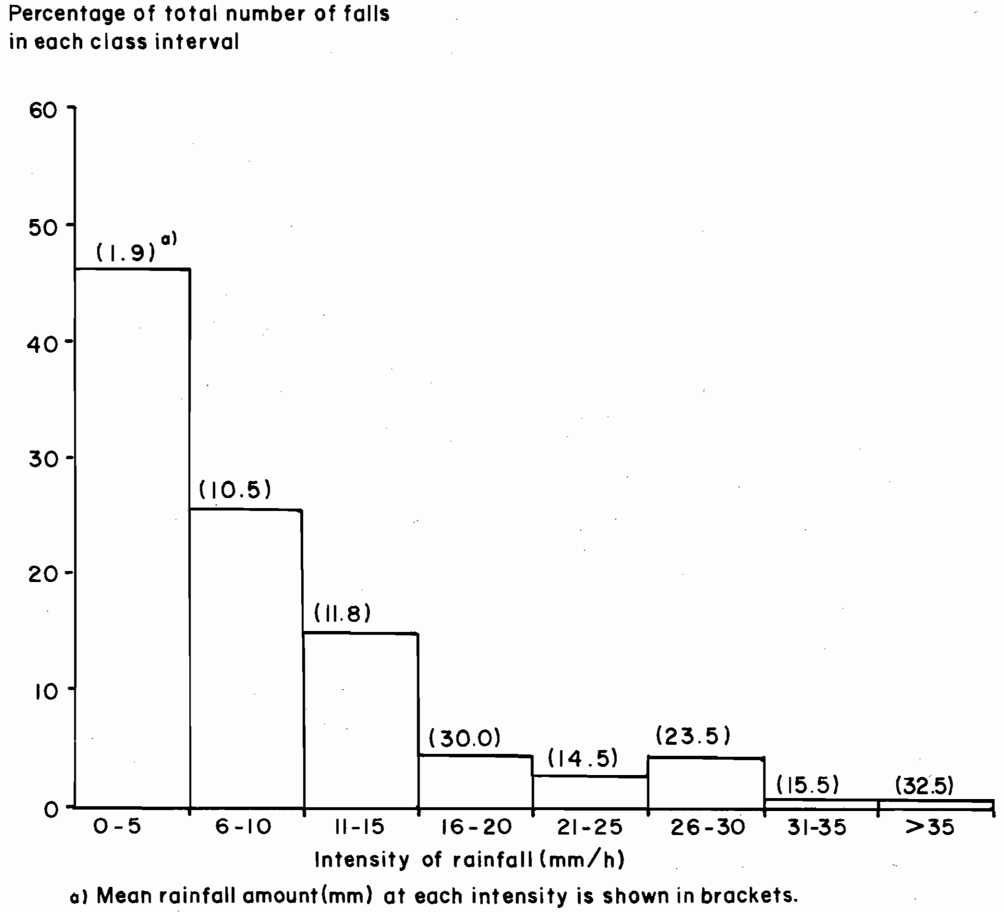
Source: Ven te Chow (1964).

Figure 8. *June maximum daily rainfall in Lagos, 1915-1926.*



Source: Ayoade (1977).

Figure 9. *Frequency distribution of rainfall intensity at Gatab, northern Kenya.*



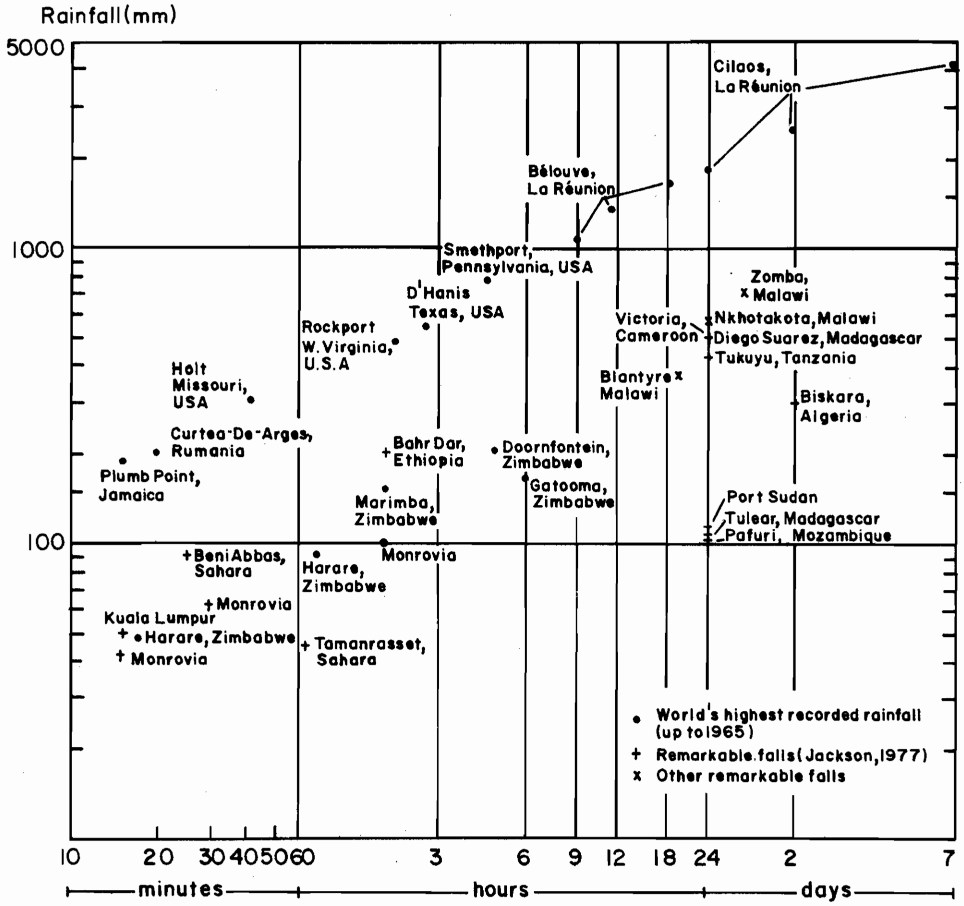
recorded at Cilaos (Réunion) were the result of an intense tropical cyclone in 1952, which was funnelled up a steep valley rising to 3000 m (Lockwood 1972). The previous world record for 24 hours was also due to the combination of tropical cyclone and land relief. On that occasion, the maximum rainfall occurred at Baguis in the Philippines following the passage of a typhoon in 1911. Less intense, but still remarkable falls of rain commented upon by Jackson (1977) are also shown on the graph.

Rainfall maxima such as those in Figure 10 only give an idea of the expected magnitude of the highest falls, with very long recurrence intervals. For general design purposes, statements about amount, duration and frequency of rainfall are required in order to compare the risk of failure of spillways, culverts and bridges against economic criteria. Such analyses can also be applied to soil erosion problems.

For a given duration, rainfall events can be ranked in either a partial duration series or an extreme value series. Thus, for daily rainfall, events can be selected so that their magnitudes are greater than a certain base value, or the maximum rainfall in any year can be chosen. Either series can be plotted on probability paper to yield recurrence intervals or return periods for a given magnitude. The difference between the two series is that the partial duration series may include several events which occur close together in 1 year. For practical purposes, the two series do not differ much, except in the values of low magnitude (Ven te Chow, 1964). An example of the annual maximum series for four stations in Tanzania is given in Figure 11. These graphs were drawn to assess the return periods of storms which caused landslides in the Uluguru Mountains in Tanzania.

Alternatively, where information from recording rain gauges is available, rainfall intensity can be plotted against duration, and intensity – duration frequency curves can be constructed for different return periods.

Figure 10. *The world's highest recorded rainfall and other remarkable falls.*



2.8 OCCULT PRECIPITATION

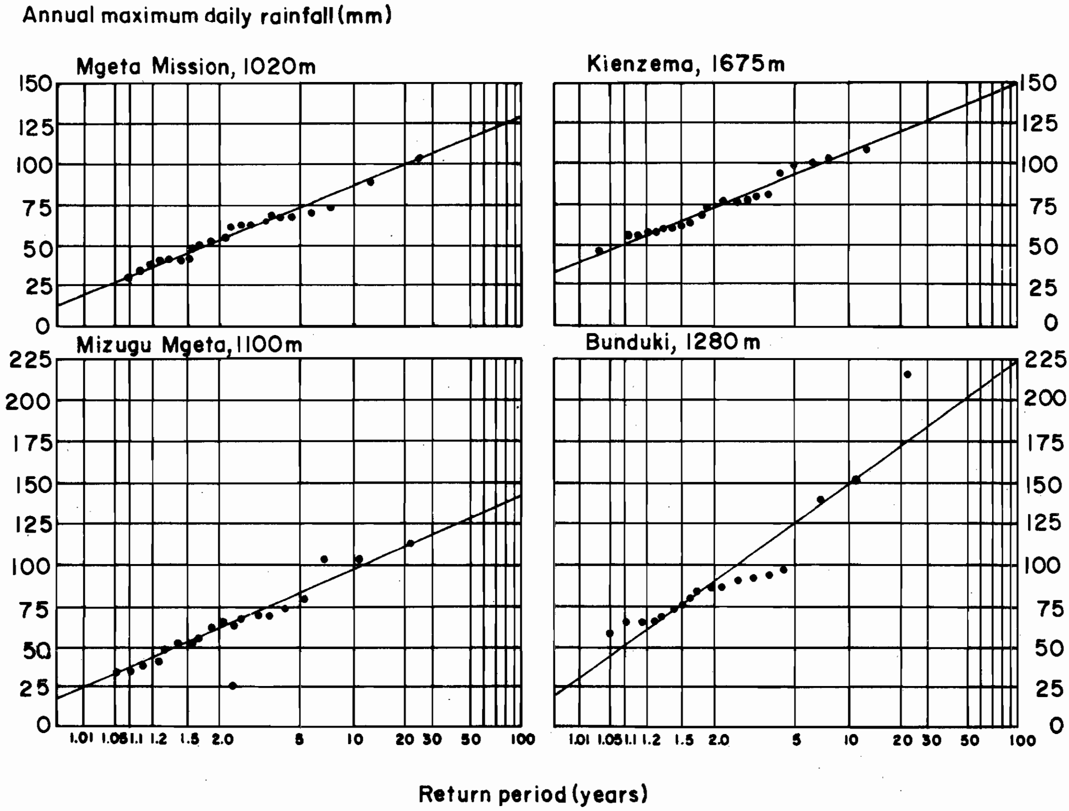
On inselbergs and mountain masses within the tropics, the summits are frequently covered in cloud in locations where the orographic uplift of moist air is sufficient to cause condensation. If the upper slopes are covered in forest, the surfaces of the leaves and branches of trees act as collectors for condensed water vapour. This phenomenon is referred to as occult precipitation, because it does not relate to any rain-making process in the cloud itself and rain gauges placed outside the forest area will not record any rainfall.

In southern and southwest Africa, Marloth (1904) and Nagel (1962) have shown that mist condensation or occult precipitation may contribute between 40 and 94% of the total precipitation on high ground. More recently, Edwards et al (1979) made some preliminary measurements on Mt. Kulal in northern Kenya and concluded that occult precipitation could be a significant addition to the groundwater store.

This mechanism may be important as a contribution to groundwater recharge and as a means of sustaining perennial basal springs on mountains in semi-arid areas. On the other hand, high rates of evaporation of intercepted water, and the deeper rooting zone of trees compared to shorter vegetation, may mean that any additional infiltrated water from occult precipitation will be rapidly used up by the trees.

Persistent and subjective reports of springs drying up following deforestation, and flowing again following reafforestation, point to the value of investigating the detailed water balance of mountains in semi-arid areas. Unfortunately, the water balances are likely to be complex, with both infiltration capacities and rates of input of precipitation varying between forested and non-forested areas. Evaporation and transpiration rates are also likely to differ significantly and, because these components would need to be measured directly, projects aiming to achieve detailed water balances would require careful instrumentation.

Figure 11. *Return periods for maximum daily rainfalls in Tanzania.*



Source: Temple and Rapp (1972).

In many areas, however, summit forests are threatened by fire and by encroachment of grazing lands. If occult precipitation is a significant additional input to the water balance, it becomes increasingly important to conserve these forests. Further research into the survival of basal springs is of major importance in pastoral areas.

3. THE HYDROLOGICAL CYCLE AND ITS COMPONENTS

3.1 THE HYDROLOGICAL CYCLE

The preceding chapter has dealt with the input to the hydrological cycle – rainfall – and its variation in time and space in response to various climatic factors. This chapter attempts to explain what happens to the rainfall once it reaches the ground. The science of hydrology is concerned with quantifying the various components into which rainfall is partitioned, and understanding the physical processes by which water is eventually returned to the atmosphere.

The cycle through which rainfall passes before being returned to the atmosphere is termed the 'hydrological cycle'. It is very complex and imperfectly understood. The cycle can be, and has been, modified radically in many places by man's activities. It is subject to the vagaries of rainfall input and to climatic change. On the other hand, great strides have been made during the last 35 years in determining the nature of the physical processes and their interactions.

From an understanding of the hydrological cycle, quantitative estimates of the various components enable simple 'water balances' to be drawn up. It is in quantifying former unknowns in the hydrological cycle that experimental scientists have made the most progress. At the same time, analytical hydrologists have been remarkably successful in modelling the cycle – or approximations of it – both by conceptual and empirical models. Forecasting and prediction now can be accomplished successfully within acceptable errors of estimation. The value of such models, however, is dependent on the quality of input data. Thus, in areas of inadequate or inaccurate data it is not always possible to model the cycle with confidence.

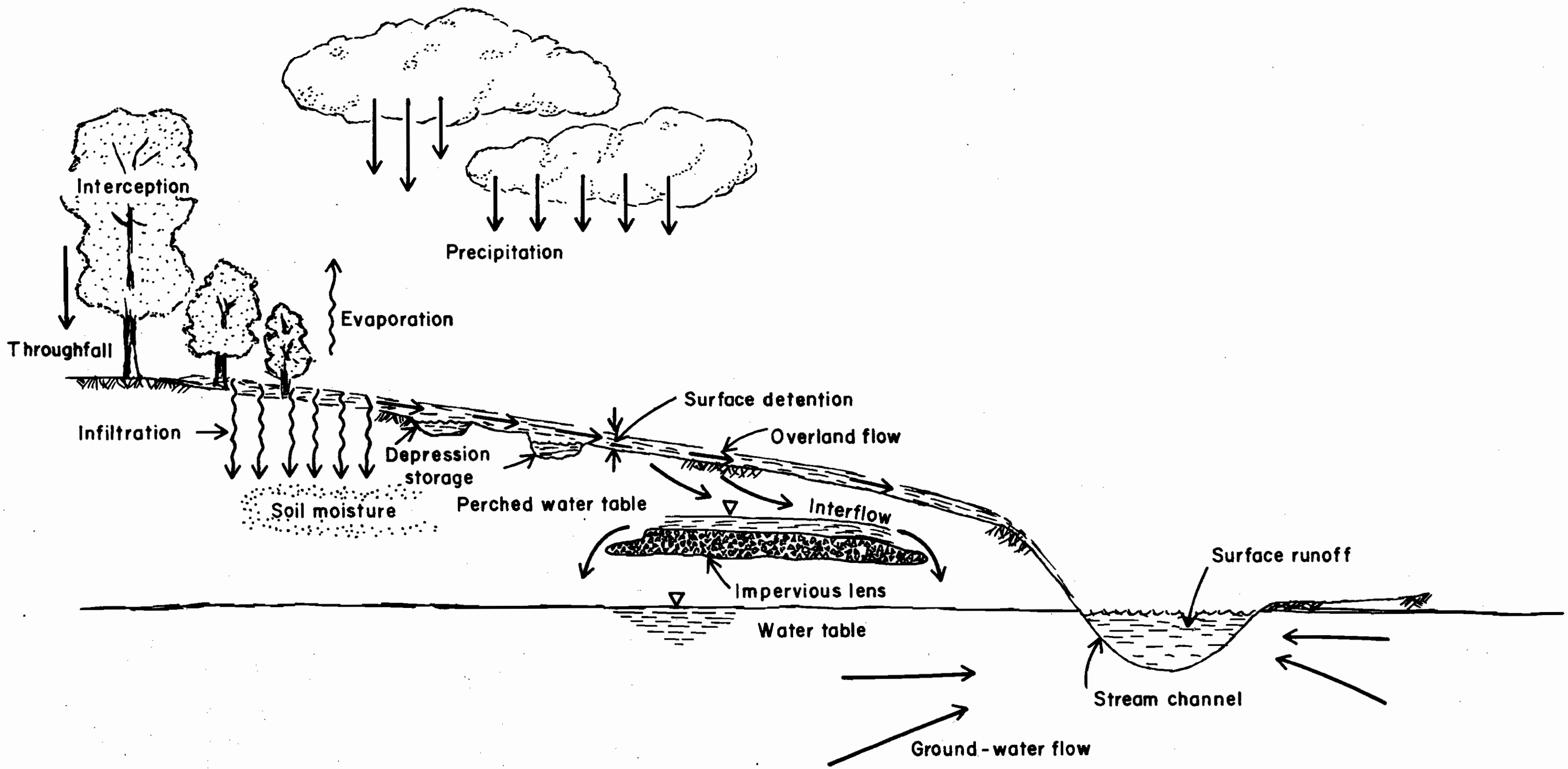
Examples of diagrammatic representations of the hydrological cycle can be found in most textbooks. Figure 12 is presented here because it emphasises the subsurface components which are often neglected. A conceptual or systems representation of the cycle is given in Figure 13, since this helps to simplify the relationships between components. Table 3 gives approximate values of the amount of water stored at various stages in the cycle. Of the world's total water resources 94% are locked in the oceans and seas, at a high level of salinity, and in ice caps and glaciers. Of the remaining 6%, Freeze and Cherry (1979) estimate the relative volumes available as a utilisable resource as: groundwater 95%; lakes, swamps, reservoirs and river channels 3.5%; and soil moisture 1.5%.

Although the percentage for groundwater points towards it being the most important component of the cycle, it is not always the most accessible source of usable water. It is frequently mineralised or polluted and, if extracted in large quantities, can cause subsidence or saline intrusions. In the tropics, large areas are deficient in surface water, and therefore use of the subsurface resource becomes a necessity. Before discussing the exploitation of the various resources, however, it is important to consider the relationship between the different components of the cycle, in order to estimate those quantities which are difficult to measure directly. An example is groundwater recharge, which has a profound bearing on the renewable character of the resource.

3.2 INTERCEPTION AND INFILTRATION

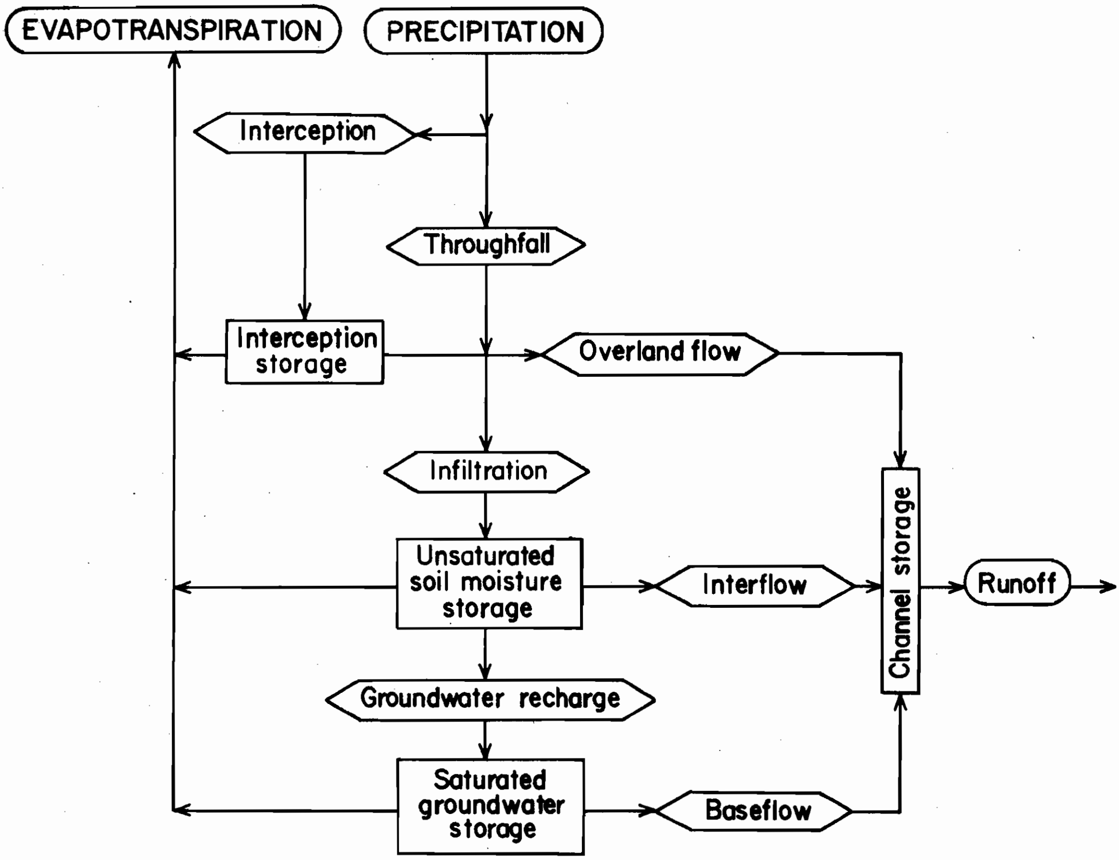
Foresters have always observed the phenomena of interception and throughfall, but few have been prepared to acknowledge that these components were of great significance in the context of the hydrological cycle. Recent work (Stewart, 1977) has established that interception can play a major role in the water balance of catchments where the aerodynamic component of the energy balance is large relative to net radiation. In the

Figure 12. *Diagrammatic representation of the hydrological cycle.*



Source: Davis and De Wiest (1966).

Figure 13. *A systems representation of the hydrological cycle.*



Source: Freeze and Cherry (1979).

tropics this is not likely to be the case, but there are indications that, even in forests lying practically astride the equator, evaporation of intercepted water can be a significant feature (Blackie, 1972; Blackie et al, 1979).

Intercepted moisture, stored in the canopy, is the first component of the hydrological cycle to be lost directly back to the atmosphere. In areas of high wind speed, with aerodynamically 'rough' canopies, this loss can be very rapid and, in areas where the canopy is frequently wetted, the total quantity of intercepted water lost by evaporation can be a significant proportion of the total rainfall. Interception of raindrops by canopies is also a major factor in reducing soil erosion. This has an indirect effect on the hydrological cycle, in that, by conserving surface soil, infiltration is maintained.

In areas of shorter vegetation interception storage is likely to be small, and the rate of loss may not exceed the potential evaporation rate. Thus in rangelands, interception storage is unlikely to be a measurable quantity in the water balance. Many dry-season grazing areas, however, depend on perennial springs for water supply. These springs emanate from hillsides covered in vegetation, where interception protects the slopes through which the springs are being recharged. Throughfall, stemflow and drip (including the so-called occult precipitation described in Section 2.8) form the precipitation input. In dense canopies throughfall is of minor importance, and hence the rate at which water is received by the soil surface is within its infiltration capacity. Surface runoff is practically nil on the heavily forested slopes, and deep percolation is often rapid, through fractured or weathered bedrock. These advantages in terms of recharge, however, have to be offset against the transpiration of deep-rooted, perennial vegetation which tends to produce moisture deficits in the root zone. These deficits inhibit deep infiltration until sufficient rain falls to saturate the root zone.

Table 3. *Estimate of the water balance of the world.*

Parameter	Surface area ($km^2 x 10^6$)	Volume ($km^3 x 10^6$)	Volume (%)	Equivalent depth (m)[a]	Residence time
Oceans and seas	361	1370	94	2500	~4000 years
Lakes and reservoirs	1.55	0.13	<0.01	0.25	~10 years
Swamps	<0.1	<0.01	<0.01	0.007	1 – 10 years
River channels	<0.1	<0.01	<0.01	0.003	~2 weeks
Soil moisture	130	0.07	<0.01	0.13	2 weeks – 1 year
Groundwater	130	60	4	120	2 weeks – 10 000 years
Icecaps and glaciers	17.8	30	2	60	10 – 1000 years
Atmospheric water	504	0.01	<0.01	0.025	~10 days
Biospheric water	<0.1	<0.01	<0.01	0.001	~1 week

[a] Computed as through storage were uniformly distributed over the entire surface of the earth.

Source: Nace (1971).

Over most of the rangelands in tropical Africa infiltration is the key process in the hydrological cycle. Infiltration capacity (Horton, 1933) or infiltrability (Hillel, 1971) define the rate at which water can enter the soil. Horton recognized both a maximum and a minimum infiltration capacity of soils; the maximum being at the onset of rainfall with the capacity decreasing as the impact of raindrops changes the surface structure of the soil (Baver, 1965). Philip (1969) has approximated the physical process of infiltration by means of the equation:

$$I = St^{\frac{1}{2}} + Kt$$

where

I = infiltration volume at time t;

S = sorptivity, a parameter proportional to the square root of the water diffusivity and to the increase in soil water content during infiltration; and

K = hydraulic conductivity of the soil.

For a more rigorous description of the infiltration process see Philip (1969), Hillel (1971) and Morel-Seytoux and Khanji (1974). Clack and Larson (1981) give a discussion of modelling infiltration.

When the rate of rainfall exceeds the infiltration capacity of the soil, the result is surface runoff, unless the surface water is stored in depressions (surface or depression storage). Thus, management for soil conservation is directed both at maintaining high infiltration rates by preserving a good surface cover, and at increasing surface storage by pasture furrows, cut-off ditches, and range pitting or water spreading (Hudson, 1971).

One of the additional problems in grazing areas is that of 'puddling'. Puddling is the structural change associated with mechanical stress while soils are in a moist condition, and results in the destruction of large pores in the soil through which water percolates. This has the effect of decreasing infiltration capacity and increasing surface runoff. Further mechanical sorting results, together with the removal of organic material and, often, surface sealing (Thomas et al, 1981). In fact, these authors found that from different types of land use in a catchment in Machakos, Kenya the greatest loss of soil was from degraded grazing areas. Much of this can be attributed to loss of vegetation from overgrazing and the downward spiral of poor vegetation leading to high rates of soil loss and surface runoff (Hudson, 1971).

With some soils, subsoil permeability may be the limiting factor in determining infiltration rates (Greenland, 1979). While this points to surface management being less important, experimental evidence shows that the compaction of well structured surface layers in tropical forest soils, such as that following clearing, causes infiltration capacity to drop by half.

Although infiltration can be seen to be a key process in the cycle, very few experimental data are available to quantify infiltration capacity. It is known to be (spatially) highly variable, and for this reason isolated measurements are of little practical benefit. Indirect evidence of the improvement of infiltration, following the re-establishment of grass cover, can be found in Edwards and Blackie (1981), who report the results of the Atumatak catchment experiment in Karamoja, Uganda from 1959 to 1970. Two adjacent degraded catchments were chosen for this experiment. One was fenced, cleared of secondary bush and subjected to a controlled grazing-density scheme. The other continued under uncontrolled grazing conditions. Soil moisture tension blocks were installed at a number of sites and, from an analysis of the measurements (Table 4), it was clear that, in the post-clearing phase, infiltration penetrated down to a depth of 60 cm at most sites. A corollary to the recovery in infiltration in the cleared catchment was the reduction in storm run-off to half that in the 'control' catchment – a striking example of rapid recovery following a modest management programme.

3.3 EVAPORATION AND TRANSPIRATION

The problem of measuring evaporation from open water surfaces, and transpiration from different types of vegetation, has been a central problem in hydrology for many years. In terms of the hydrological cycle and the water balance, evaporation and transpiration make up the second largest component. Errors in estimating evaporative loss, therefore, assume great significance, for example, in the calculation of groundwater recharge.

Difficulties in understanding the physical nature of the evaporation process, together with ambiguous results from the various types of instrument designed to measure evaporation directly (such as evaporation pans and evaporimeters), led to the development of empirical techniques for estimating evaporation, using generally available climatic data (Thornthwaite, 1948; Blaney and Criddle, 1950; Turc, 1955). These techniques were recognized and acknowledged to give only approximate estimates, but in the absence of simple-to-apply, more theoretically sound methods they provided a useful means of calculating irrigation need and consumptive water use by crops.

Advances in micro-meteorology have produced more sophisticated techniques for measuring evaporation. Generally speaking, these are still research techniques requiring far more instrumentation or experimental data than are normally available.

Perhaps the best compromise is the semi-empirical but physically based formula of Penman (1948; 1952; 1956; 1963), or its many derivatives (Monteith, 1965; Thom and Oliver 1977). This embodies the concepts of 'potential transpiration' (ET) from vegetation plentifully supplied with water, and of 'open-water evaporation' (EO) from an extensive open-water surface. The original formula (Penman, 1948) is a combination of the energy balance and aerodynamic methods of measuring evaporation. The energy quantities available for evaporation and for heating the soil-plant-atmosphere system can be equated:

$$R_n = \lambda E + K + G$$

where

R_n = net radiation,
λE = latent heat flux,
K = sensible heat transferred to the air, and
G = sensible heat transferred to the soil.

In tropical regions G becomes small in relation to R_n over a day, and may be neglected. R_n can be measured or estimated from incoming solar radiation (R_c), or hours of bright sunshine (Glover and McCulloch, 1958), and the problem becomes that of partitioning R_n between sensible heating of the air and the latent heat flux.

The ratio $K/\lambda E$ is known as the Bowen ratio (β). Penman derived an estimate for β by introducing an empirical aerodynamic term Ea and eliminating the need to measure surface temperatures. Evaporation from an open-water surface (EO) is then given by:

$$EO = \frac{\Delta H + \gamma Ea}{\Delta + \gamma}$$

where

Ea = $f(u)\,(1 + u_2/100)\,(e_a - e_d)$,
H = $(R_n - G)\,\lambda$,
Δ = the slope of the curve relating saturation vapour pressure to air temperature at mean air temperature,
γ = the psychometric constant,
$f(u)$ = an empirical constant,
u_2 = run-of-wind at 2 m height above the ground, and
e_a, e_d = saturation vapour pressure at air temperature and dew point respectively.

On the basis of the Lake Hefner experimental results (US Navy, 1952), Penman modified the aerodynamic term to:

$$Ea = f(u)\,(0.5 + u_2/100)\,(e_a - e_d)$$

justifying the correction on the grounds that the new term gave better agreement with evaporation from a large body of water (Penman, 1956).

To estimate ET, Penman first used a reduction factor which varied seasonally. Averaged over the whole year, a value of 0.75 was derived for western Europe. At a later stage, making use

Table 4. *Frequency of rainfall penetration during land-use experiments at Atumatak, Uganda.*

	Year	Mean number of readings	Depth (cm)							
			15	30	45	60	90	120	180	240
Pre-clearing	1959	*A*[a] 31	38	38	10	6	13	0	0	0
		B[a] 31	38	18	4	8	0	0	0	0
	1960	*A* 48	47	43	19	11	21	14	0	0
		B 50	44	35	7	21	0	0	2	0
	1961	*A* 48	66	59	52	39	30	12	17	17
		B 49	62	48	32	38	12	12	4	4
Mean for pre-clearing phase, 1959-1961		*A*	50	46	27	18	21	9	6	6
		B	48	34	14	22	4	2	2	1
Values for clearing phase, 1962-1963	1962	*A* *B*	Very few readings							
	1963	*A* 44	48	37	31	38	13	18	52	32
		B 43	50	50	38	45	35	23	14	9
Post-clearing	1964	*A* 48	22	15	9	13	1	3	6	3
		B 47	32	34	18	12	4	2	0	0
	1965	*A* 31	19	19	12	9	0	0	0	13
		B 31	27	18	13	17	0	0	0	0
	1966 1967 1968		Very few readings							
	1969	*A* 46	8	4	4	3	0	0	0	0
		B 43	19	19	11	15	1	0	2	0
	1970	*A* 50	20	19	16	14	1	2	0	8
		B 53	44	42	37	41	1	0	2	0
Mean for post-clearing phase, 1964-1970		*A*	17	14	10	10	0	1	2	6
		B	30	26	19	21	22	1	1	0

[a] *B* is the cleared catchment and *A* the control.

Figures indicate the mean percentage frequency with which available moisture was indicated by the resistance blocks.

Depths of runoff and rainfall for a sample of storms (*n*) at Atumatak.

		Catchment *A* (control, untreated)			Catchment *B* (bush-cleared)		
	n	*Q*[b] (mm)	*R*[b] (mm)	*Q/R* (%)	*Q*	*R*	*Q/R* (%)
Bush-clearing, 1959-1961	59	70.73	678.8	10.4	76.02	785.9	9.7
During clearing, 1962-1963	53	65.40	838.3	7.8	135.44	868.0	15.6
After clearing, 1964-1968	61	160.09	1109.1	14.4	74.86	1092.8	6.8

[b] Q = runoff; R = rainfall.

of measurements of the albedo of grass, and reinstating the original aerodynamic term to take into account the aerodynamic roughness of short vegetation, a one-step formula was introduced:

$$ET = \frac{\Delta H + \gamma Eat}{\Delta + \gamma} \qquad \text{(Penman, 1963)}$$

where

$Eat = f(u)\,(1 + u_2/100)\,(e_a - e_d)$, and
$H = (R_n - G)/\lambda$, with R_n now measured over grass.

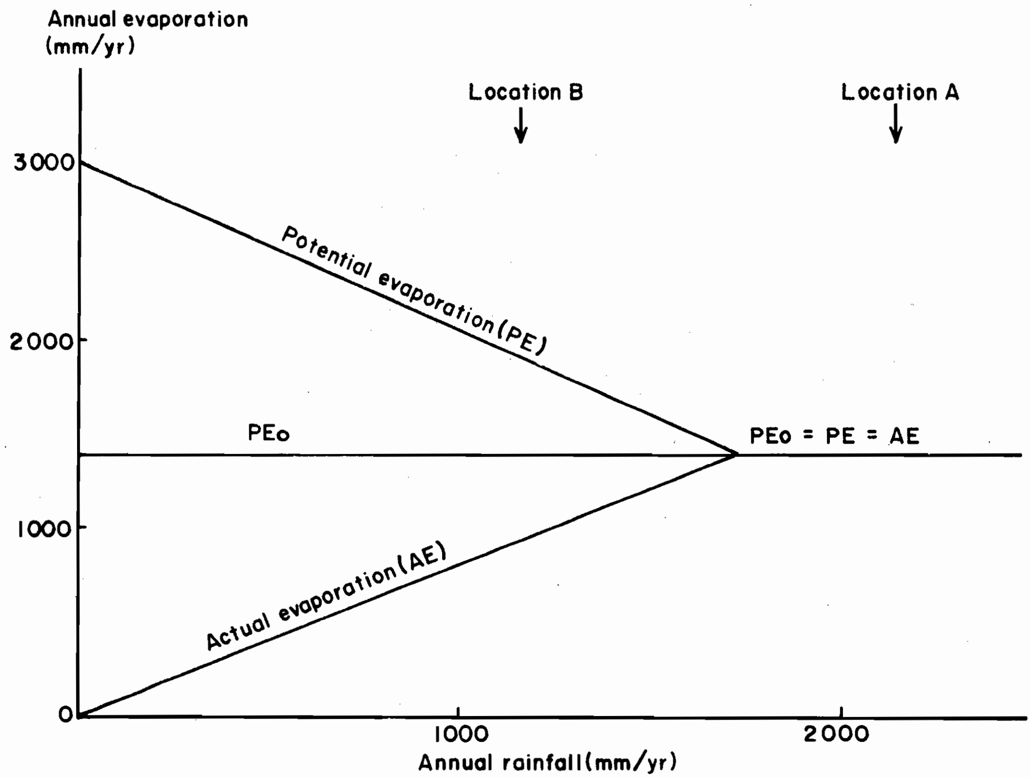
This formula has been used to provide an index of evaporation. In practice, it can be expected to give reasonable estimates of ET within the accuracy of the other components of water balance, where water supply to the root zone is not a limiting factor (Edwards and Rodda, 1970; Blackie et al, 1979). Regional maps of potential evaporation have been produced for Kenya (Woodhead, 1968a), Tanzania (Woodhead, 1968b) and Uganda (Rijks et al, 1970), and the formula is now widely used in modelling the water use of crops (Doorembos and Kassam, 1979).

Simplified calculation methods for the Penman formula can be found in McCulloch (1965), Berry (1964) and Doorembos and Pruett (1977). Further modifications of the approach can be found in Monteith (1965) and Thom and Oliver (1977).

Where water supply to the root zone is a limiting factor, as in most of the semi-arid tropics, actual evaporation (AE) is considerably less than potential evaporation (PE). The direct methods of measuring AE require complex and expensive equipment, and the indirect methods, such as the water balance of watertight catchments, do not give short-period water use unless soil moisture measurements are available.

An alternative approach has been developed by Bouchet (1963), and embodies the concept of complementary evaporation. Broadly speaking, this concept states that the difference between AE at a dry site and PE at a wet site, subject to the same radiation input (where water supply is not limiting), is the same as the difference between PE estimated at the dry site (i.e. with the same radiation input but lower humidities and higher air temperatures) and PE calculated for a wet site. This can best be illustrated by a diagram (Figure 14), in which annual evaporation is plotted against annual rainfall. The theoretical values of PE are seen to decrease with increasing rainfall at the drier site (location A) until they reach a value PE_o, which is a function of radiation input,

Figure 14. *Relationship between actual evaporation, potential evaporation and annual rainfall.*



temperature and humidity, where soil moisture is not limiting (location B). Variations in the theoretical values of AE are the precise opposite, increasing with increasing rainfall until they reach the same limiting value of PE_o.

Brutsaert and Stricker (1979) used the Priestley-Taylor equation (Priestley and Taylor, 1972) to calculate PE_o. The formula which was developed to estimate evaporation in the absence of advection reads:

$$PE_o = \frac{1.26\Delta\ R_n}{\Delta + \gamma}$$

They used the Penman formula to estimate the local potential evaporation (PE_B). AE can now be found from the Bouchet relationship:

$$AE = 2PE - PE_B$$

This approach was tested by Stewart et al (1982), together with an improved Penman formula incorporating a larger aerodynamic term (Thom and Oliver, 1977). They found, using data from 120 tropical stations, that the method is only valid when used with climatological data recorded at sites further than 50 km from a coast. At these stations the modified Brutsaert and Stricker formula gave encouraging results, which support the concept of complementary evaporation. Clearly the approach has great potential in areas of sparse data.

3.4 GROUNDWATER

The infiltration characteristics of the land surface and the rainfall intensity and duration determine the rate at which the soil moisture store is replenished. After consumptive use by vegetation, a small proportion drains under gravity to the groundwater store. The occurrence of subsurface water can vary according to soil type, the nature of the underlying parent material and the depth of weathering. A classification of subsurface water is given in Figure 15. Water is held in each zone as a result of gravitational surface tension and chemical forces. There are no sharp boundaries, except at the capillary fringe in coarse-grained sediments. The water table is, in fact, a theoretical surface, and can be demonstrated approximately by the level of water in wells which penetrate the saturated zone. The water table can be defined as the level at which the fluid pressure of the pores, in a porous medium, is exactly atmospheric. Below the water table the subsurface water is usually termed groundwater. It can exist in the rock pores to very great depths (ca. 3000 m), but in dense rock the pores are not interconnected and the water will not migrate.

Only a small proportion of the zone of saturation will yield water to wells. The water-bearing portions are called aquifers. Many types of formation can serve as aquifers, a key requirement being the ability to store water in pores.

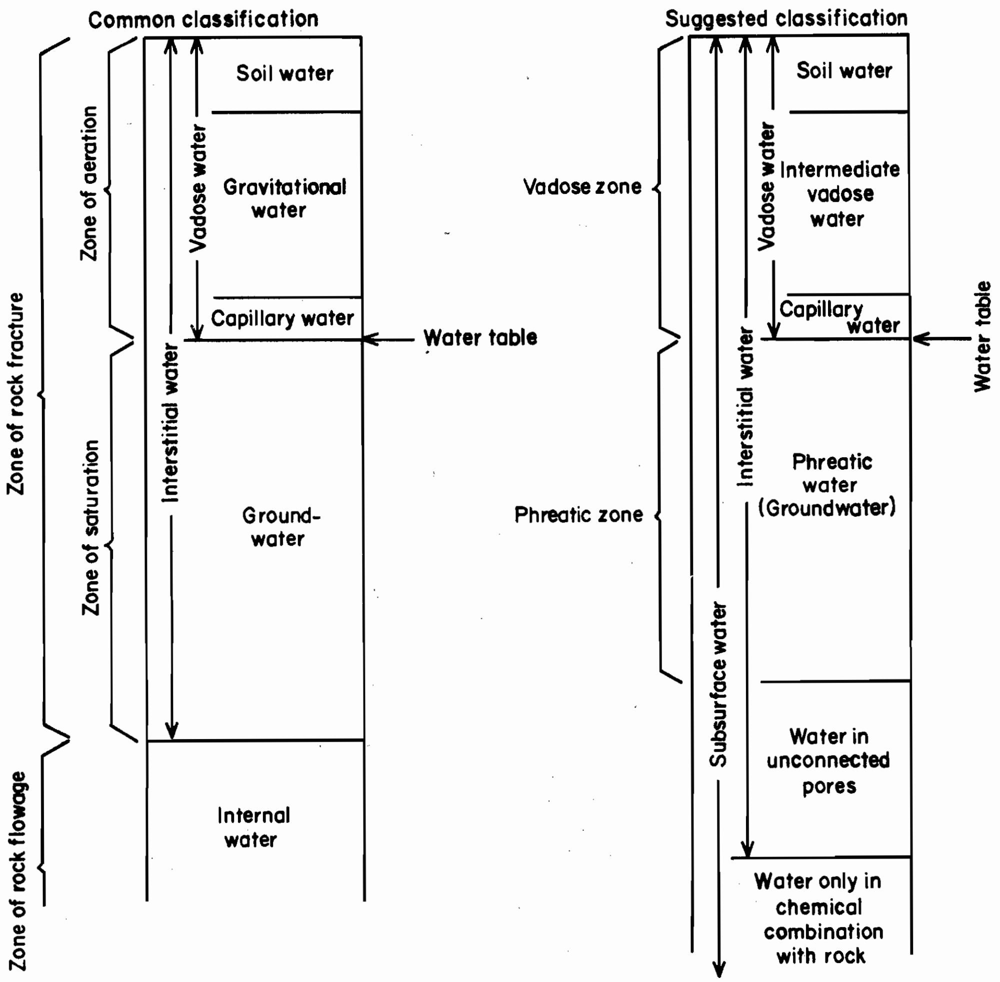
Table 5 gives a typical range of values of porosity, and it is clear that the unconsolidated deposits (chiefly sands and gravels) are the most important aquifers. Pores in the silts and clays are too small. Volcanic rocks are often good aquifers because of the many types of opening which contribute to their permeability. Igneous and metamorphic rocks are generally regarded as poor aquifers but, over large parts of Africa, the Precambrian basement rocks are near the surface and are deeply weathered. These form shallow aquifers of low yield (0.5 to 1 l/sec), sufficient for small domestic supplies and stock watering. The areal extent of the basement complex rocks on the old erosion surfaces makes this type of aquifer extremely important in the context of tropical Africa. Joints and fractures in the crystalline basement hold some water, but storage is usually quite small and recharge is from the surface weathered zone. Therefore, yields tend to be less than or equal to those from the shallow surface aquifers.

Table 5. *Typical porosity values for different formations.*

Aquifer type	Porosity (%)
Unconsolidated deposits	
Gravel	25–40
Sand	25–50
Silt	35–50
Clay	40–70
Rocks	
Fractured basalt	5–50
Karst limestone	5–50
Sandstone	5–30
Limestone, dolomite	0–20
Shale	0–10
Fractured crystalline rock	0–10
Dense crystalline rock	0–5

Aquifers may be classified as confined and unconfined, according to whether or not the water is separated from the atmosphere by impermeable material. Confined aquifers often give rise to artesian wells, where the pressure within the aquifer is sufficient to produce flowing wells at the surface. Unconfined aquifers, of course, have water whose upper surface is at atmospheric pressure. The term semiconfined is used for the inter-

Figure 15. *Classifications of subsurface water.*



Source: Davis and De Wiest (1966).

mediate condition, where the confining layer is not completely impermeable. Often lenses of unconfined water are encountered above the water table, held by isolated layers of impermeable material. These are termed perched aquifers and the upper surface is a perched water table.

Groundwater may be discharged at the surface or into bodies of surface water. Springs are the most noticeable manifestation of this, but seepage into rivers and lakes is also an important part of the hydrological cycle. Artificial discharge is induced by well digging or borehole drilling. The exploitation of groundwater by these techniques is dealt with in Chapter 6.

The quantity of discharge is a function of the porous medium, which is related to the size and interconnection of the pores. The storage term for unconfined aquifers is the 'specific yield' – defined as the volume of water released from storage per unit surface area of aquifer, per unit decline in water table. The storage coefficient in confined aquifers is the 'storativity' – defined as the volume of water released per unit surface area of aquifer, per unit decline in the component of hydraulic head normal to that surface (Freeze and Cherry, 1979).

In the context of the hydrological cycle, groundwater flow passes from recharge areas to discharge areas. Fluctuations in the water table introduce transient effects in the flow system. However, it can often be simulated as a steady-state system if the fluctuations in water table are small in comparison with the total vertical thickness of the system (Freeze and Cherry, 1979).

Discharge areas in semi-arid climates can be mapped by the direct field observation of springs and lines of seepage, or by the occurrence of phreatophytes and other distinctive vegetative patterns. An analysis of the lithology, topography and existing borehole data will also give information on the recharge – discharge regime and allow the application of steady-state water balance equations to the surface and subsurface components within the recharge and discharge areas.

This approach is often applied to determine the recharge potential within a catchment area and, although livestock requirements are generally very small in comparison with the recharge components, it is a useful exercise to balance all the measured components in order to determine gross errors, or to assess the possible effects of a management programme.

3.5 RUNOFF

Within the pastoral regions of tropical Africa most streams and rivers are seasonal or ephemeral with only the larger rivers, which rise in heavily forested, highland or plateau areas, being able to sustain perennial flow.

Seasonal and ephemeral streams are characterised by having hydrographs with a very rapid rise to peak discharge within a short time of rain, and a still rapid but more gradual recession, so that a large proportion of the total flow occurs in about the first 2 hours of rainfall.

The volume of storm runoff depends to a large extent on the antecedent soil moisture conditions and the intensity of rainfall. Typical annual runoff volumes in semi-arid areas, expressed as a percentage of rainfall, would be less than 10%, but individual storms can produce much higher runoff volumes (ca. 70%) when rain falls in an already saturated catchment. Runoff varies widely according to the seasonal distribution of rainfall, catchment characteristics (shape, size, steepness), vegetation type and density, in addition to the two basic criteria mentioned above.

Table 6 shows the annual runoff, expressed as a percentage of annual rainfall, for large catchments in Kenya. Table 7 shows similar percentages for smaller catchments in Malawi. Table 8 gives numerous examples of annual runoff coefficients from the Niger, Congo, Zambezi and Nile basins (Balek, 1977). Figure 16 is a graph of annual runoff coefficients for individual storms against the catchment size for West African stations (Rodier, 1977). Generally speaking, the wide variation of annual totals makes it difficult to predict total catchment yield from rainfall alone. Most attempts to regress runoff against rainfall lead to unacceptable scatter.

Actual measurements of runoff and rainfall, on the other hand, can yield acceptable values of annual AE in watertight catchments, where groundwater storage changes very little from year to year. In heterogeneous catchments a general value for AE may not have much validity, but careful measurements, particularly of rainfall, in small homogeneous catchments have led to some of the best estimates of AE (Blackie et al, 1979).

While total runoff or streamflow gives the yield of water from a particular catchment in a particular year, it is closely dependent upon variations in annual rainfall. As in the case of rainfall, a set of runoff data can be subjected to a frequency analysis and statements can be made about the probability of occurrence of certain values.

More usually, however, interest is centred on the extremes of exceptionally high or low annual runoff events and their duration. In these cases, partial duration series or annual maximum (or minimum) series plotted on extremal probability paper will give the recurrence intervals of particular events.

To obtain the duration of annual flows above or below certain limits, an entirely different technique is required. This relies on rainfall being a stochastic process, where the annual rainfall in a

Table 6. *Annual runoff as a percentage of rainfall – Kenya.*

Drainage area	Mean annual rainfall (mm)	Mean annual runoff (mm)	Runoff/Rainfall (%)
Lake Victoria	1245	149	12
Rift Valley	535	6	1
Athi River	585	19	3
Tana River	535	36	7
Ewaso Ngiro	255	4	2
Average for Kenya	500	25	5

Table 7. *Annual runoff as a percentage of rainfall – Malawi.*

River	Mean annual rainfall (mm)	Mean annual runoff (mm)	Runoff/Rainfall (%)
Ruo	1280	395	31
Kwakwazi	1240	332	27
Likangala	1430	499	35
Domasi	1730	882	51
Naisi	1280	312	24
Linthipe	880	133	15
Lilongwe	930	155	17
Lingadzi	810	82	10
Bua	900	83	9
Bua	900	73	8
Dwangwa	740	37	5
Luweya	1480	500	34
Luchelemu	1090	260	24
Lunyangwa	1210	232	19
N. Rumphi	1320	661	50
Kambwiya	1370	625	46
N. Rukuru	910	227	25

particular year is independent of the rainfall in preceding years. Although irregular trends and spells of wetter-than-average or drier-than-average rainfall are commonplace, most attempts to discern reproducible cycles or harmonic patterns in rainfall have failed. In the absence of demonstrable cycles there is no reason to assume that the irregular patterns are other than those which could be expected to occur in an entirely random series from time to time.

It is possible to extend a data set having characteristic statistics of mean and variance by generating a similar sequence of random values. This can be repeated many times and the actual occurrence of runs of values above or below certain limits can be analysed. A good example of this technique in practical use is described by Kidd (1983), who used it to generate synthetic or theoretical inflows into Lake Malawi in order to predict outflow down the Shire River and the effects of controlling outflow with a barrage.

Often, as in the case of designing small water supplies, the seasonal variations in daily flow are important. The best way to represent these is by means of a flow-duration curve. This is a cumulative frequency curve of daily flows, expressed as a percentage over as long a period as possible. Figure 17 gives an example of such a curve for daily flows compared with typical curves for monthly and annual mean discharges (USGS, 1959). Thus, it is possible to estimate the percentage of time during which a given flow is equalled or exceeded.

In the case of low flows duration of flow is particularly important. It is often necessary to know what the minimum flow would be over a certain time with a given level of occurrence. Thus for a water supply scheme, 30 days might be the absolute maximum that either stock or people could survive on storage. The 5-year, 30-day minimum flow can be compared with the demand to see what supplementary measures (boreholes, shallow wells) are necessary, on average, in a 5-year period.

This statistic and other comparable statistics (e.g. 10-year, 60-day minimum flow) can be calculated by a frequency analysis of overlapping 'n'-day flows in a given run of data. This is best performed on a computer because of the amount of data involved. Where a long dry season occurs, as in much of tropical Africa, a visual inspection of the recession curves of the streams is usually sufficient to gain some idea of the frequency of very low flows of specified duration.

It is necessary to know the peak flow or flood for the design of any structure intended to pass a given volume of water per unit time (e.g. spill-

Table 8. *Annual runoff as a percentage of rainfall – Niger, Congo, Zambezi and Nile basins.*

River	Location	Drainage area (km^2)	Precipitation (mm)	Runoff (mm)	Runoff coefficient (%)	Mean annual discharge (m^3/s)
	Water balance of Niger basin					
Niger	Sigiri	70 000	1640	420	25	931
Interbasin	Sigiri-Koulikouro	50 000	1424	393	28	624
Niger	Koulikouro	120 000	1550	409	26	1555
Interbasin	Koulikouro-below mouth of Bani	102 600	1235	235	19	770
Niger	below Bani	222 600	1405	328	23	2325
Interbasin	Bani-Benue	501 400	964	35	4	532
Niger	above Benue	724 000	1100	126	11	2877
Benue	mouth	319 000	1495	343	23	3477
Niger	below Benue	1043 000	1221	192	16	6354
Interbasin	Benue mouth of Niger	48 000	1880	375	20	571
Niger	mouth to Gulf of Benin	1091 000	1250	198	16	6925
	Water balance of Congo basin					
Chambeshi	above Bangweulu Swamps	43 830	1143	241	21	337
Interbasin	Bangweulu Swamps	57 664	1229	59	5	110
Luapula	below Bangweulu Swamps	101 494	1191	138	12	441
Interbasin	Bangweulu S.-Mweru L.	71 372	1165	136	12	307
Luapula	at Mweru L.	172 866	1181	138	12	754
Kalungwishi	Mweru (mouth to)	26 696	1143	164	14	139
Interbasin	Kalungwishi-Lualaba	123 734	1160	132	11	520
Luvua	Confluence with Lualaba	296 600	1172	136	12	1274
Lualaba	Uzilo	16 300	1100	200	18	103
Lufiva	Cornet Falls	11 980	1180	126	11	48
Lualaba	above Luvua	187 800	1130	110	10	651
Lualaba	below Luvua	484 400	1156	126	11	1931
Interbasin	Luvua-Lukuga	7 200	1125	108	10	24
Lualaba	above Lukuga	491 600	1155	125	11	1955
Lukuga	mouth to Lualaba	270 900	1062	32	3	271
Lualaba	below Lukuga	762 500	1122	91	8	2226
Interbasin	Lukuga-Lowani	277 083	1905	602	32	5295
Lualaba	above Lowani	989 583	1399	239	17	7521
Lowani	mouth	95 830	1675	274	16	837
Congo	confluence Lowani-Lualaba	1085 413	1422	249	17	8358
Interbasin	confluence Ubangi	463 000	1875	482	26	7126
Congo	above Ubangi	1548 413	1559	315	20	15 484
Ubangi	mouth	754 830	1597	248	16	5936
Congo	below Ubangi	2303 243	1569	293	19	21 420
Interbasin	Ubangi-Sanga	9580	1750	355	20	108
Congo	above Sanga	2312 823	1561	293	19	21 528

Table 8. *Continued.*

River	Location	Drainage area (km^2)	Precipi-tation (mm)	Runoff (mm)	Runoff coefficient (%)	Mean annual discharge (m^3/s)
Sanga	mouth	213400	1580	362	23	2471
Interbasin	Sanga-Kwa	109500	1750	375	21	1304
Congo	Kwa	2635723	1581	301	19	3303
Kwa	mouth	881887	1538	350	23	9873
Congo	below Kwa	3517610	1570	314	20	25176
Interbasin	Kwa-mouth of Congo	89840	1300	220	17	629
Congo	mouth	3607450	1561	313	20	38805
	Water balance of Zambezi basin					
Zambezi	Chavuma Falls	75967	1288	231	18	555
Interbasin	Chavuma Falls-Chobe	284538	1030	61	16	541
Zambezi	above Chobe	360505	1085	95	9	1096
Chobe	mouth	870758[a]	625[b]	3	1	135
Zambezi	below Chobe	1231263	760	30	5	1231
Interbasin	Chobe-Vict. Falls	5317	605	21	3	6
Zambezi	Victoria Falls	1236580	759	30	4	1237
Interbasin	Victoria F.-Kafue	163380	718	54	8	261
Zambezi	above Kafue	1399960	754	34	5	1498
Kafue	mouth to Zambezi	154856	1023	85	8	417
Zambezi	below Kafue	1554816	782	38	5	1915
Interbasin	Kafue-Luangwa	19091	1198	25	2	151
Zambezi	above mouth Luangwa	1573907	787	41	5	2066
Luangwa	mouth	148326	925	91	10	436
Zambezi	below Luangwa	1722233	799	44	6	2501
	Water balance of Nile basin					
Victoria Nile	Ripon Falls	269000	1302	81	6	699
Semliki	above confluence with Victoria Nile	22500	1395	88	6	63
Albert Nile	below Albert Lake	281500	1309	85	6	762
Interbasin	Albert Lake-Mongalla	184500	1228	20	2	111
White Nile	Mongalla	466000	1277	60	5	874
Interbasin	Mongalla-Sobat	438800	900	−38	–	−511
White Nile	above Sobat	904800	1094	12	1	362
Sobat	mouth	187200	1081	71	7	431
White Nile	below Sobat	1092000	1091	22	2	793
Interbasin	Sobat-Blue Nile	343000	500	0	0	0
White Nile	above Blue Nile	1435000	710	16	2	793
Blue Nile	confluence with W. Nile	324530	1082	158	15	1727
Nile	below confluence with Blue Nile	1759530	778	43	6	2420
Interbasin	confluence Aswan	79470	1080	97	9	244

Table 8. *Continued*

River	Location	Drainage area (km^2)	Precipitation (mm)	Runoff (mm)	Runoff coefficient (%)	Mean annual discharge (m^3/s)
Nile	Aswan	1839 000	790	45	6	2664
Interbasin	Aswan mouth	1042 000	7	–18	–	71
Nile	mouth	2881 000	506	28	6	2593

[a] with Northern Kalahari

[b] Chobe basin only, 798mm

Source: Balek (1977).

ways on dams, culverts, canals and bridges). Many empirical and analytical techniques are available to predict floods. It is outside the scope of this report to discuss more than the general principles. Readers interested in this topic will find a comprehensive treatment of the subject in NERC (1975), in spite of the direct relevance of this report to British conditions. The proceedings of the symposium on 'Flood hydrology' (TRRL, 1977) deals specifically with African conditions, and applies similar techniques of flood prediction to both urban and rural catchments.

Basically, a choice can be made between empirical techniques based on catchment characteristics, statistical techniques (where there is an abundance of reliable data), and unit-hydrograph techniques (which require some knowledge of rainfall characteristics, soil types, channel slope and shape of the unit hydrograph).

Figure 18 shows a flow diagram for the process of estimating a design flood using either the statistical or the unit-hydrograph approach. For further details NERC (1975) should be consulted.

In many areas throughout tropical Africa there are insufficient streamflow records for statistical techniques to be applied with confidence. Usually statements are required about ungauged catchments where a large degree of uncertainty is bound to arise. Choice of method depends to a large extent, therefore, on the amount and type of data available. It is still common to find the so-called 'rational method' being applied where sufficient data for other methods are lacking (Prabhakar, 1977). In this method, maximum runoff (Q_{max}) is related to average rainfall intensity (I) and catchment area (A) by means of an empirical runoff coefficient (K):

$$Q_{max} = K.I.A$$

Values of K are derived locally, often by trial and error, and values for Kenya conditions are given in Table 9.

Another method, used when data are lacking, is the 'envelope curve' method in which recorded peak flows are plotted against catchment area. Figure 19 shows such a curve for Kenya (Prabhakar, 1977). Although a remarkable degree of conformity is often found, it is not possible with this method to relate magnitude to frequency of occurrence; but from experience, the line marked A-B in the diagram is expected to give approximately the 25-year flood.

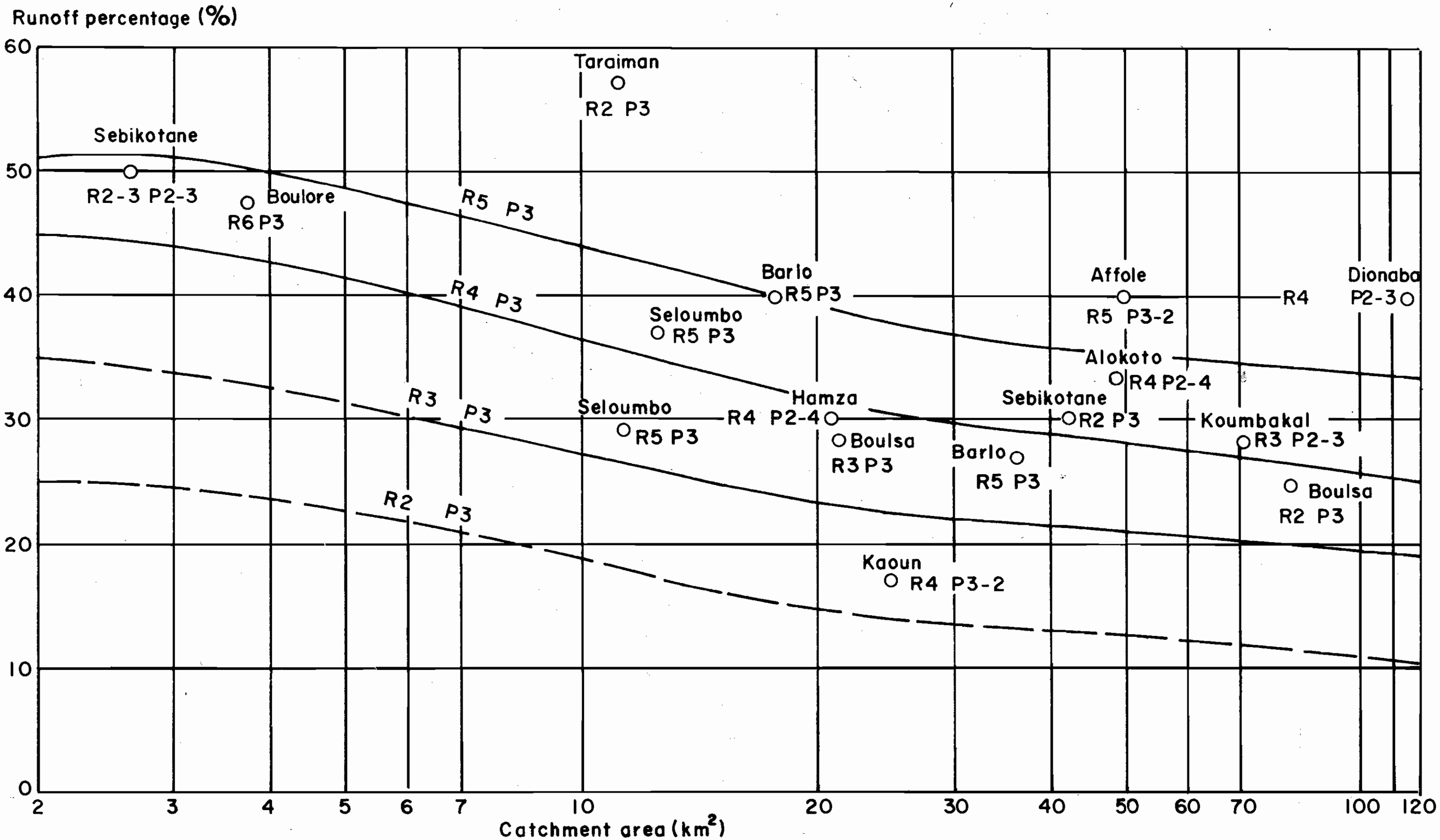
Implicit in many analyses of streamflow is a division between surface runoff, or storm runoff, and baseflow. As the name implies, surface runoff is the direct runoff from the soil surface to the stream course, concentrated by the shape of the catchment and the drainage network into a flood wave which reaches a maximum and then attenuates as it travels down the main river. Baseflow, on the other hand, is conventionally taken as the contribution to streamflow from groundwater. After the passage of the flood wave, the catchment slowly drains until the flow in the river is related to the amount of water held in storage within the catchment. The 'recession curve', the

Table 9. *Empirical values of the factor K in the rational formula.*

Type of catchment	Empirical values of factor K
Rocky and impermeable	0.30 to 1.00
Slightly permeable, bare	0.60 to 0.80
Slightly permeable, partly cultivated or covered with vegetation	0.40 to 0.60
Cultivated absorbent soil	0.30 to 0.40
Sandy absorbent soil	0.20 to 0.30
Heavy forest	0.10 to 0.20

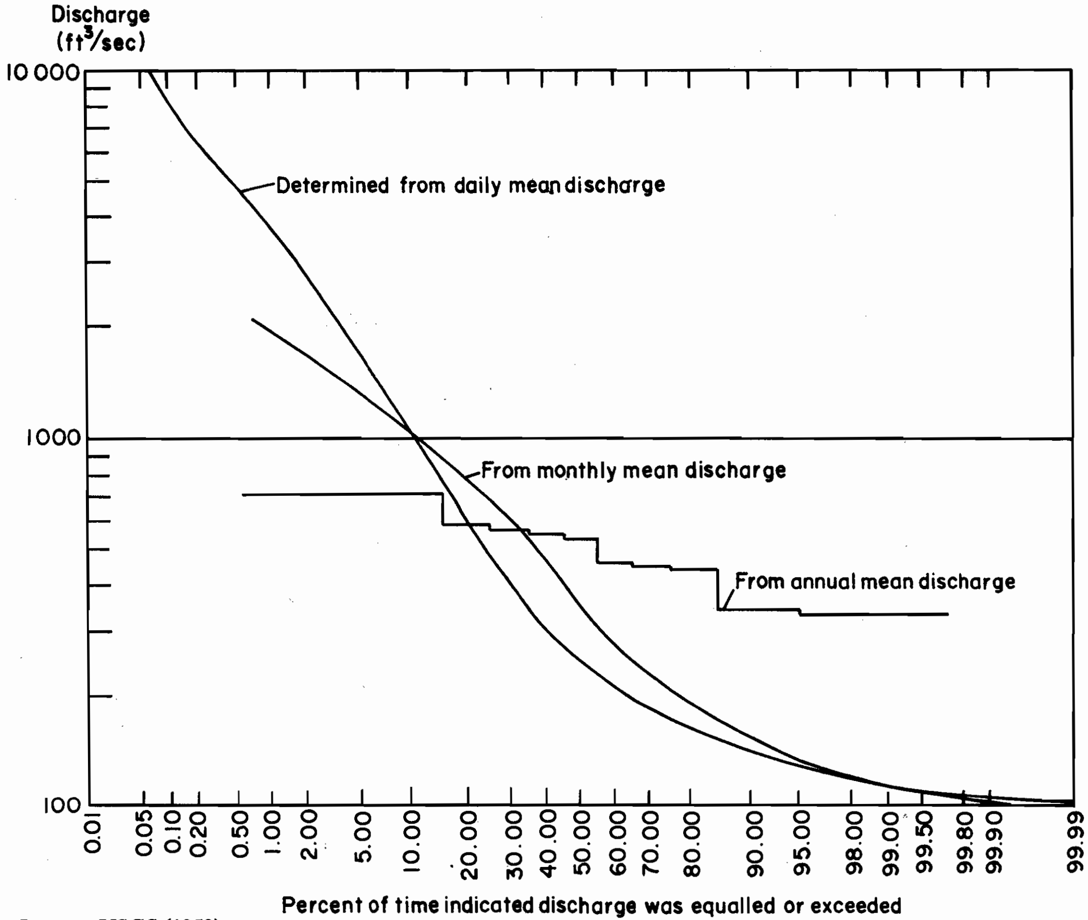
Source: Prabhakar (1977).

Figure 16. *Annual runoff coefficients for West Africa.*



Source: Rodier (1977).

Figure 17. *Flow-duration curves for daily, monthly and annual flows, Bowie Creek nr. Hattiesburg, Mississippi, 1939-1948.*



Source: USGS (1959).

slowly falling limb of the hydrograph, therefore, reflects the rate of release of water from the groundwater store, which is itself dependent upon a combination of hydraulic head and saturated permeability of the catchment. The exponential shape of a recession curve allows 'recession constants' to be calculated. These in turn can be used to predict the amount of water in the groundwater store, since the physical process of releasing water from storage can be simulated by a linear 'reservoir' (in systems terminology) whose outflow is directly related to storage:

$$Q_t = Q_o K_r^{\,t}$$

where

Q_t = flow at time t after Q_o, and

K_r = recession constant.

The storage (S_t) remaining in a basin at time t is given by:

$$S_t = -\ Q_t/\ln K_r$$

The recession constant can be used, therefore, both to separate stormflow and baseflow (by extrapolating backwards in time from the recession limb of the hydrograph), and to estimate the groundwater storage at a given time. The latter technique is often used in water balance calculations, as will be seen below.

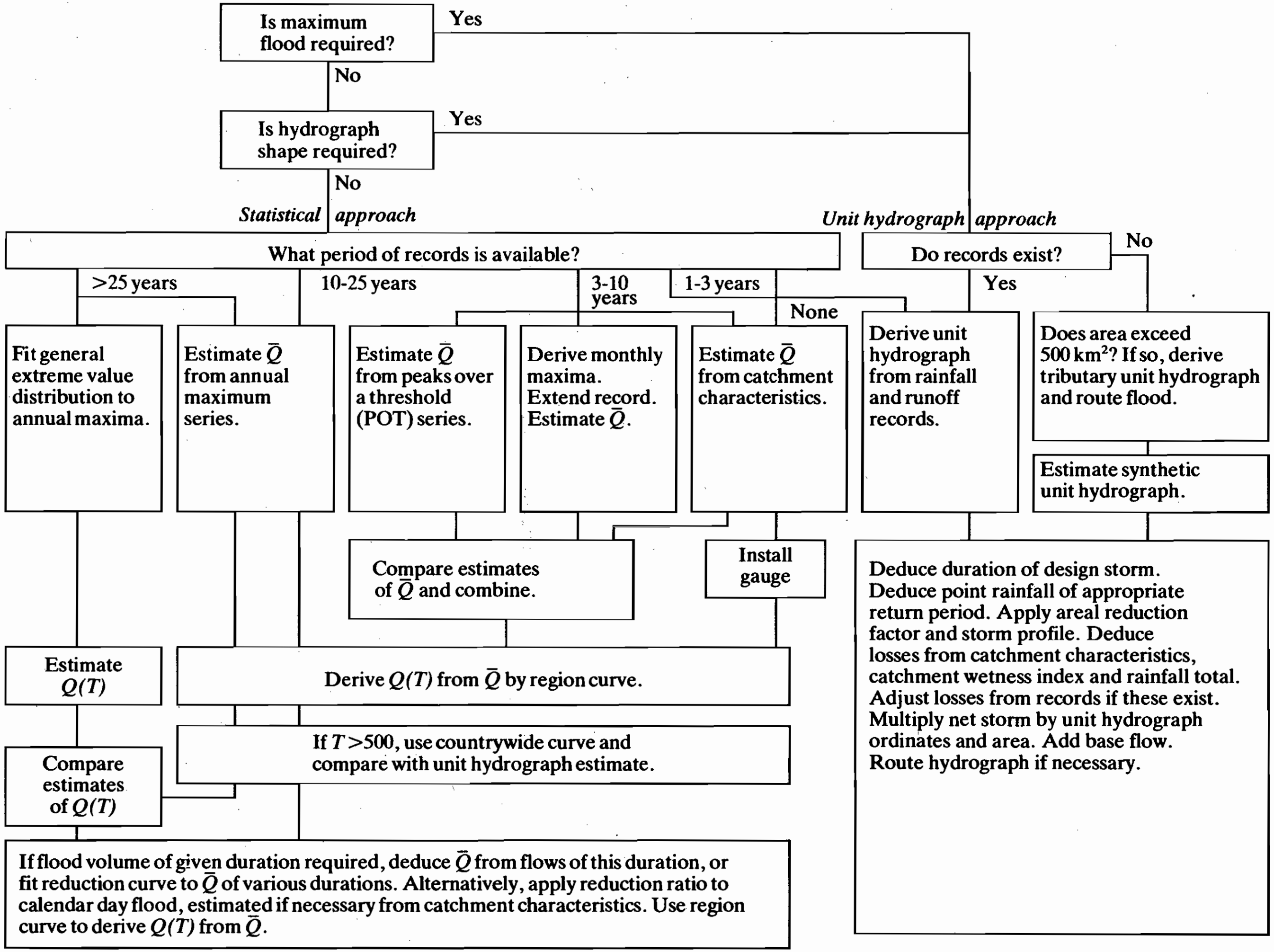
3.6 MEASUREMENT OF STREAMFLOW

Although hydrometric networks in tropical Africa have improved over the past 30 years, the majority of gauging stations are still on large rivers or in areas of high agricultural potential, where information is required for water supply and/or irrigation.

In the rangelands not only are networks sparse, but the preponderance of shifting controls (e.g. sandy river beds), coupled with infrequent visits, lowers the reliability of the streamflow records.

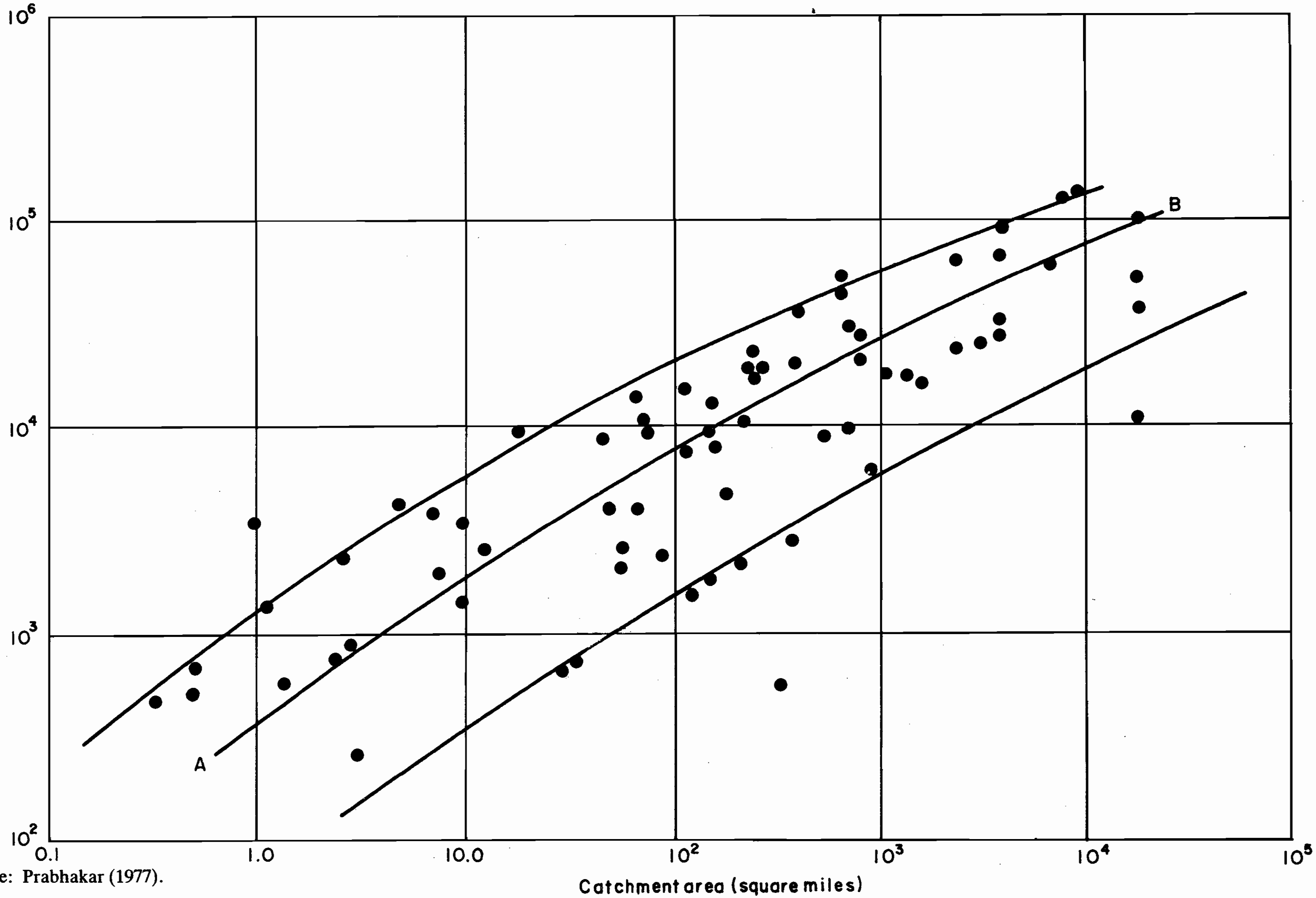
In ungauged catchments, which are often of very small size, it is frequently necessary to estimate either storm runoff or streamflow. Once

Figure 18. *Flow diagram for estimating design floods.*



Source: NERC (1975).

Figure 19. *Envelope curves for maximum floods observed in Kenya, 1930-1962.*



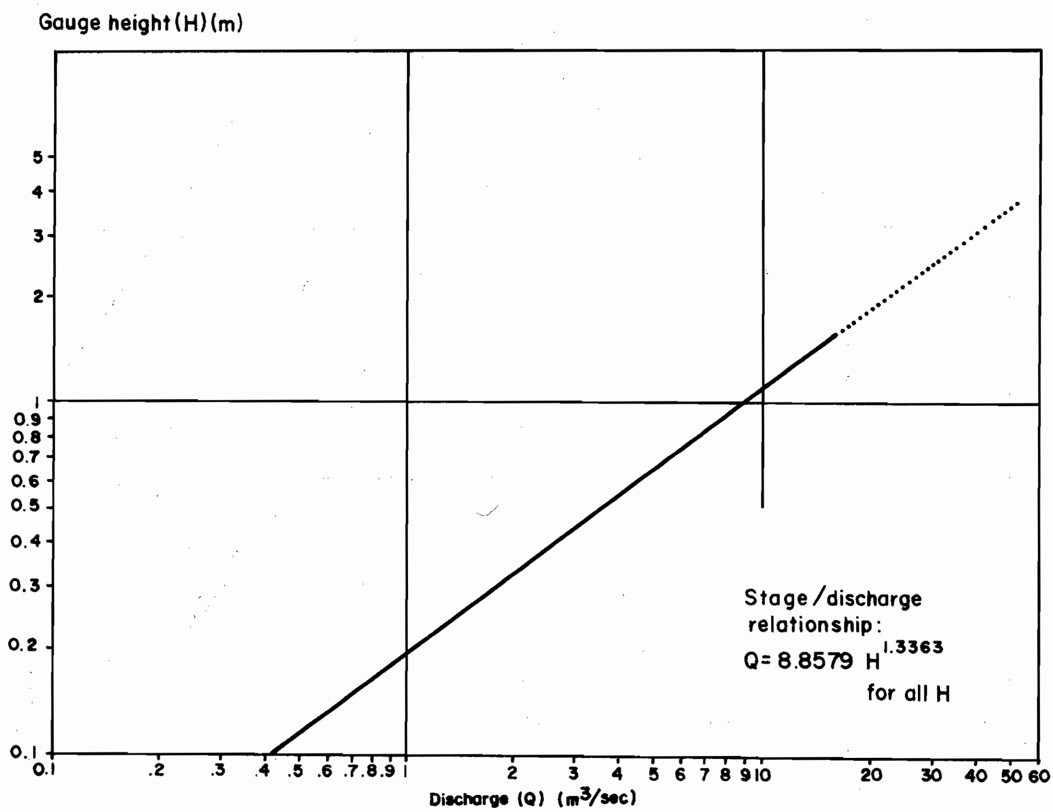
Source: Prabhakar (1977).

again there is a choice of methods, depending on the type of information required and the availability of data from nearby stations within the same hydrological region. These range from the statistical, analytical and empirical techniques referred to in the last section to mathematical models of various degrees of complexity, which are dealt with later in this report. However, the actual measurement of streamflow is better than the most sophisticated indirect methods, although usually a combination of the two is used to derive estimates of frequency or reliability.

Measuring the flow in a river is straightforward if the river is shallow enough for wading. The basic problem is that of obtaining a unique relationship between height of the water above a datum and discharge. Weirs and flumes are structures which stabilise the channel section to give this unique relationship. For very small streams with a discharge up to 0.12 $m^3 . sec^{-1}$, portable "v"-notch weirs can often be installed (British Standards Institution, 1965), which will measure discharge (flow per unit time) for a given depth of flow over the weir. Where the benefits to be accrued do not warrant the construction of weirs or flumes, the natural channel has to be 'calibrated'. This is achieved by making a series of measurements of discharge, using a current meter, at different 'stages' (i.e. at different heights of water above the zero-flow datum). These values can be plotted on a graph of discharge against stage (Figure 20), to give a smooth curve (the 'storage-discharge' or 'rating' curve). This curve can be extended using the Manning formula, which relates discharge to the slope of the channel and its conveyance (Ven te Chow, 1964). Once the rating curve is established, continuous or periodic measurement of a stage can be readily converted into discharge.

The choice of channel section is important in order to ensure, as far as possible, that the flow remains uniform, and that a 'control' governs the stage-discharge relationship throughout its range by eliminating the effects of downstream channel features. Such controls can be rock bars or constrictions of the stream channel which are characterised by having pools or smooth reaches upstream. Where such natural constrictions do not exist, long, straight reaches with stable beds should be sought. It is possible with the latter,

Figure 20. *Stage/discharge curve for the Mkuti River, Tanzania.*



Source: NORCONSULT (1981).

however, that the control may be drowned out at high flows causing a change in the stage-discharge relationship.

Where a river is carrying a lot of sediment, changes in the channel cross-section will occur from time to time. These will affect the stage-discharge relationship, and will call for frequent measurements of discharge with a current meter to ascertain what error is being introduced into the discharge calculations by assuming a single rating curve. Often several rating curves will have to be used where a channel is eroding or silting up rapidly (Figure 21).

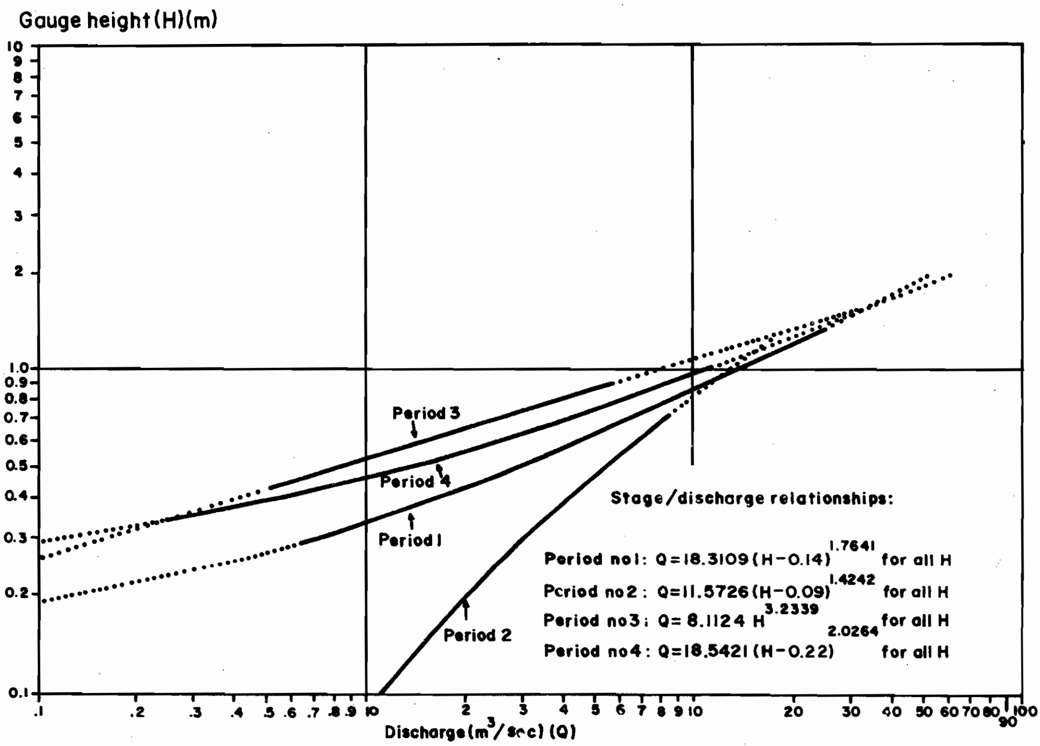
For a full discussion of the techniques for measuring streamflow the Norwegian Agency for International Development (NORAD) has produced a series of manuals on operational hydrology (Tilren, 1979) for the use of the Tanzanian Ministry of Water, Energy and Minerals. Other users would find these manuals full of sound practical information which could be applied throughout tropical Africa.

3.7 EROSION AND SEDIMENTATION

No discussion of surface water in tropical Africa would be complete without reference to erosion and sedimentation. In the humid tropics good management can usually succeed in maintaining a protective vegetative cover. In the semi-arid areas there is a delicate seasonal balance between available moisture and vegetation cover. The slightest change in this balance can begin a chain reaction of removal of cover, surface sealing, decreased infiltration, increased surface runoff, less soil moisture available for plant growth etc. With the removal of vegetation, surface soils are quickly removed by the impact of intense rainstorms and are readily transported by surface runoff. Flow concentrates into rills, rills into gulleys, gulleys into stream bank erosion; until large quantities of material are being transported as either suspended sediment or bed load. Within a very short time all the nutrient bearing soil horizons are removed, leaving pavements of rock fragments or other large particles which are too heavy to remove by raindrop impact and surface runoff.

This change can be induced by climatic factors, by man, or more usually by a combination of both. Some experiments have shown that the process can be partially reversed by simple management techniques (Bogdan and Pratt, 1967). It does not necessarily follow, however, that a recovery of vegetation will lead to a complete recovery of infiltration rates and of available water

Figure 21. *Stage/discharge curve for the Kaseke River, Tanzania.*



Source: NORCONSULT (1981).

capacity. The hydrological regime may be irreversibly changed, with serious consequences for seasonal availability of streamflow.

Another feature of accelerated erosion is the destructive power of rivers in flood. Changes in course, undermining of embankments, bridges or spillways, and the destruction of vegetation or of human habitations are commonplace throughout the semi-arid tropics. In the wake of the destructive flood wave, flows decrease, following the pattern of the recession limb of the hydrograph. Gradually decreasing velocities cause the river to drop its charge of sediment, rapidly filling up surface water reservoirs, diversion weirs, irrigation channels and any water control features. The effects of erosion and deposition, therefore, must be taken into account in any development of surface water resources. Clearly, there is little point in investing in surface water in a catchment which is suffering from accelerated erosion until a management plan for soil and water conservation is implemented over the whole catchment. In marginal areas the expense of implementing such a plan would certainly rule out the surface water option.

The measurement of sedimentation (embodying the processes of erosion, entrainment, transportation and deposition) is a complex subject, and one of the best summaries of the 'state of the art' can be found in the manual on *Sedimentation Engineering* produced by the American Society of Civil Engineers (ASCE, 1977). The financial cost of damage produced by sedimentation in the United States of America is enormous. The total average damage from deposition in 1948 was quoted in the above text as being US$ 174 000 000, and the average annual flood damage as US$ 100 657 000 for the 20-year period between 1925 and 1944. This gives some idea of the magnitude of the problem in a region where erosion control programmes are active. It is impossible to say what the figure would be for damage to agricultural land, cost of maintenance or impairment of the capital value of irrigation and drainage enterprises, damage to storage reservoirs used for power, water supply, irrigation, flood control and multiple purposes in the African continent as a whole. The impact on food and animal production must also be very great and, yet, it is still extremely difficult to focus attention and to channel development funds into soil and water conservation.

3.8 THE WATER BALANCE

The general expression describing the water balance of a watertight catchment over a given period is:

$$R = Q + AE + \Delta S + \Delta G$$

where R, Q are precipitation and streamflow respectively and can usually be measured directly;

AE is actual evaporation and transpiration; and

ΔS, ΔG are changes in soil moisture and groundwater storage respectively.

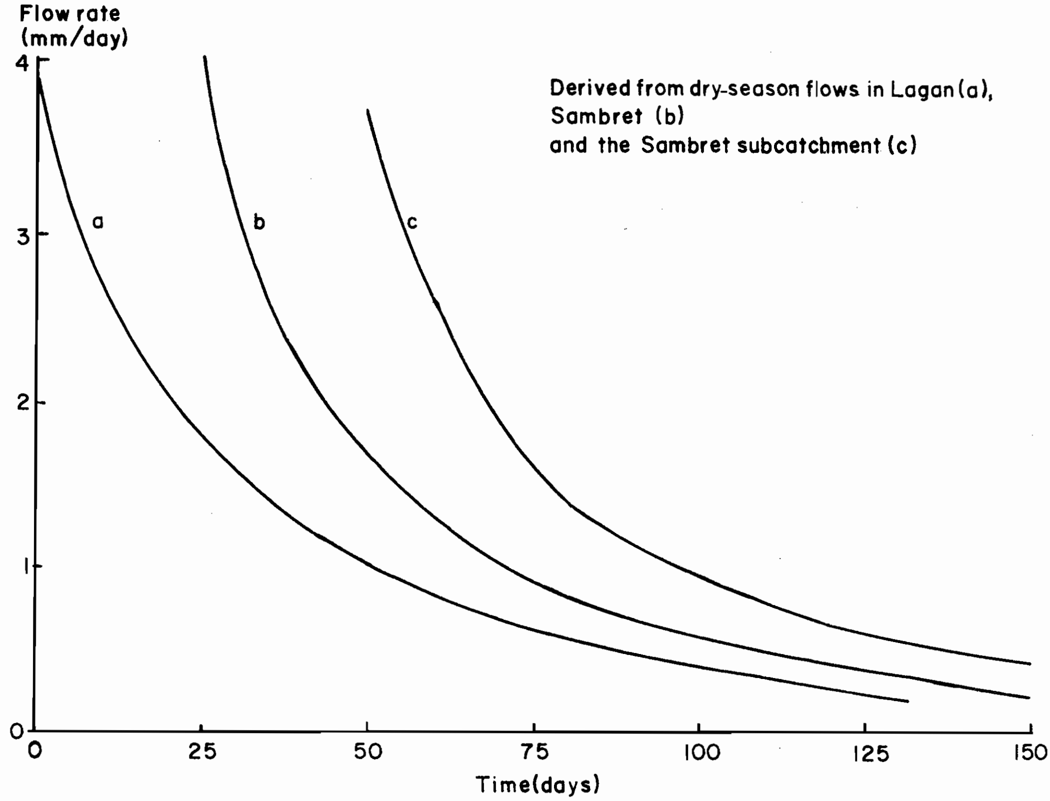
Where no bias is present in any of the measured terms this expression can be used to determine the value of any one term, by difference, over a given period. There will be a random error present, of course, which is dependent on the precision of the instruments, the efficiency of the sampling networks and the extent to which ΔS or ΔG can be measured in the catchment.

In regions which experience a long dry season the differences from year to year between soil moisture storage at the end of the dry season are usually very small. Similarly, groundwater storage tends to return to a minimum storage state at the end of the dry season. Exceptions occur when the groundwater store drains out excessively during a drought period. On return to wet conditions a proportion of the storage input is required to top up the stores to a more usual state. Conversely, during a very wet period the groundwater storage is not depleted so fully, and there is a surplus of recharge which tends to drain rapidly. These features are recognizable in the baseflow recession of the stream. By using the composite recession curve an estimate of the groundwater storage can be made (Figure 22).

As mentioned previously, the actual evaporation (AE) term is the term most commonly estimated by the water balance method (Blackie et al, 1979). By choosing a 'water year', i.e. a period of approximately 1 year running from the end of one dry season to the end of the next, consecutive estimates of annual AE can be obtained. For shorter-period estimations of AE detailed soil moisture records are required, and it is more usual to distribute the annual total according to an empirical seasonal model in the absence of direct measurements of AE.

Water balance has also been used to estimate groundwater recharge (Lloyd et al, 1967) in an arid area of northeast Jordan. The authors estimated that, on average, 8.2% of the annual rainfall reached the aquifers – which is in agreement

Figure 22. *Composite recession curves of dry-season flows for three catchments in Kenya.*



Source: Blackie et al (1979).

with two previous estimates obtained using different techniques.

If the development of a particular aquifer involves the abstraction of a quantity of water even approaching its recharge potential, the water balance should be used as an additional check to avoid overexploitation of the resource. Generally speaking, unless a large well field is contemplated for an urban area, the abstraction rates are likely to be well below the recharge potential. Israel is one country where abstraction is dangerously close to the rate of recharge, and careful monitoring of pumping is carried out along the coastal aquifers to prevent the intrusion of saline groundwater from the Mediterranean interface (Webster, 1971).

The water balance equation also provides the basic framework for mathematical modelling of the hydrological cycle. Such models are usually stochastic-conceptual (see Clarke, 1973, for a full discussion of the use of mathematical models in hydrology): 'stochastic' because the chance of occurrence of the variables is taken into consideration and the concept of probability is introduced; and 'conceptual' because the form of the model is suggested by consideration of the physical processes acting on the input variable(s) to produce the output variable(s).

The unit-hydrograph approach to flood prediction, on the other hand, may be termed a deterministic-empirical model, if all variables are regarded as free from random variation ('deterministic') and the model is formulated without reference to the physical processes ('empirical') (see O'Donnell, 1966; Dooge, 1965).

Where discharge records are short, and longer records of rainfall are available, a stochastic-conceptual model can be formulated in which the parameters are estimated for the period of common data. The longer rainfall records can then be used to extend the discharge period. Kidd (1983) gives a good example of these techniques applied to African conditions, whereas Blackie (1972) demonstrates a deterministic-conceptual model applied to the water balance of East African catchments.

Simple deterministic models can often be formulated to solve unknown variables in the water balance (Lloyd et al, 1967), but in order to introduce any element of probability (i.e. reliability), in e.g. estimating recharge or actual evaporation, it is necessary to introduce stochastic techniques unless exceptionally long periods of records are available.

Here again, the type of model must be suited to the end product desired, to the quantity and quality of data available, and to a cost-benefit analysis of exploiting a water resource with or without a knowledge of the risks involved. The need for immediate practical benefits and the lack of data usually call for the use of mathematical models in most applications to livestock development. As investment costs increase, it is wise to examine the implications of proceeding without some examination of the medium- and long-term effects of an expensive system of exploitation. An understanding of the hydrological cycle, therefore, and the quantification of the various components in the form of a water balance, should be an essential prerequisite of all large-scale management plans.

4. THE POTENTIAL WATER RESOURCE OF THE PASTORAL AREAS OF TROPICAL AFRICA

As described in Chapter 2, the pastoral areas of tropical Africa are characterised by rainy seasons of short duration, which may be unimodal or bimodal in form, during which insufficient rainfall is received to sustain arable agriculture. Although 'mixed farming' – in the temperate latitude sense – is practised in some of the more climatically favoured subtropical countries, the climatic control has tended to influence indigenous people to farm with either crops or livestock and rarely both (Philips, 1966). Thus, an ecological adjustment to the climatic environment has become 'fixed' and traditional in the course of time.

Increasing pressure from population growth has caused the replacement of relatively high-quality grasslands by crops, especially since the development of drought-resistant crop varieties; so much so that it can now be accepted that the pastoral areas are confined to those climatic zones which suffer from a seasonal deficit of rainfall of varying severity.

A prerequisite for full development of the pastoral areas, therefore, is the provision of additional and well distributed water supplies. New watering points must be sited in relation to the location and carrying capacities of available pastures (Webster and Wilson, 1966). They must be accompanied by stock control and a system of rotational grazing to prevent overgrazing. This is a management problem, of course, but the water engineer must not be allowed to make an existing situation worse, by the unplanned provision of watering points which will themselves encourage overstocking and overgrazing.

Further, it is clear from Chapter 3 that the interdependence of the components of the hydrological cycle weighs against any uncoordinated action, such as the sole provision of water supplies, since those very supplies may be dependent ultimately upon the maintenance of good infiltration rates. These in turn are a function of vegetation cover, and that cover will only remain if overgrazing is prevented.

Surface water supplies are more prone to degrade and decline due to overgrazing than are groundwater supplies because, generally speaking, stock watering requires so little water compared to the volume of recharge of groundwater. Surface water supplies, however, are usually cheaper to maintain and can be constructed without the aid of sophisticated machinery. Choice of the type of supply will depend partly on the resource potential and partly on the availability of manpower, machinery and funds for construction and maintenance. Before going on to discuss methods of using the water resource, it is helpful to consider the types of resource and their characteristics.

4.1 SURFACE WATER

4.1.1 Springs

Natural springs occur wherever the hydraulic head in an aquifer exceeds the surface elevation. Often this results in seepage around discharge areas which is revealed by vegetation changes, particularly the occurrence of phreatophytes. Where more open conduits are found springs result, often of remarkably constant discharge and of high quality. On the other hand, they can be highly mineralised, and the vast majority of springs, particularly in semi-arid areas, have discharges less than 1 l/sec. Areas of volcanic rock and sand hills are noted for their potential to contain springs of nearly constant discharge. A classic example of a large spring of high discharge is the complex at Mzima Springs in Kenya, where recharge on the volcanic Chyulu Hills is translated into a flow large enough to serve the town of Mombassa.

Basal springs from inselbergs or monadnocks, i.e. erosion residuals on the peneplain surfaces of the African continent, have been a source of water for pastoralists for many generations. Only recently has there been a serious threat to their survival as encroachment into the forested upper slopes, felling and burning have laid open the hitherto protected soils to erosion. Infiltration and recharge are the first parameters to change, but there are also more subtle effects, such as the cessation of occult precipitation and 'fog drip'.

The effects of forest removal on the survival of basal springs is a complex and controversial subject. Many people believe that forests 'attract' rainfall, with the corollary that removal of the tree cover leads to a decrease in rainfall. Attractive though this thesis is for foresters and conservationists, there appears to be little indisputable scientific evidence to support it (Penman, 1963). The dominant rainfall mechanisms are features of the general circulation but, as was discussed in Chapter 2, in the continental tropics, away from the direct influence of the trade winds, uniformity of pressure and temperature characterises large areas. Within these areas small differences in the surface energy balance may be sufficient to trigger the rainfall producing mechanism, particularly when unstable, moisture-laden air is passing over cool, transpiring areas of forest.

When the forests occur in upland areas, it is difficult to separate the effects of orographic uplift from any cooling effect due to the latent heat of vaporisation required by the transpiration process. Observable effects of forest are the increase in occult precipitation and fog drip (see Section 2.8). It is also irrefutable that forests have a vital role to play in soil and water conservation. Maintaining a forest cover ensures that recharge to groundwater takes place, although this has to be balanced against evaporation and transpiration from deep-rooted trees.

4.1.2 Streams

The distinction between a stream and a river is arbitrary both in the scientific and ordinary usage of the terms. A river is a large flow of water and a stream is a small flow, the smallest streams being the beginning of channel flow. River is also used in a generic sense, meaning a system of streams within a river or drainage basin. Both may be seasonal or perennial. Even the perennial streams and rivers originating in pastoral areas are characterised by extreme variability in frequency and volume of discharge.

In this context a stream may be defined as a natural channel flow where the catchment or drainage basin is less than 10 km^2. Peak runoffs could be expected to lie in the range of 10 to 200 $m^3.sec^{-1}$, depending on the type of soil, the slope, the degree of vegetation protection and the shape of the catchment. The larger floods would be exceptional and confined to steep, rocky and unprotected catchments. They are included here as a reminder of the immense destructive power of floods from even quite small catchments which are degraded and eroded.

Annual yield can be expected to be less than 100 mm depth over the catchment, with a marked seasonal distribution. The actual magnitude of yield has little significance except in the context of storage reservoirs. What is important is the minimum flow, as discussed in Chapter 3. This determines whether storage or a supplementary source from groundwater is required or not. For livestock watering purposes small storage reservoirs may be needed, which will almost certainly fill up in the wet season provided there is not a complete failure of rain.

Since the use of small streams depends to a large extent on their dry-season flow, it is extremely valuable to gauge the streams during the dry season, and then to assess the reliability of that flow from an analysis of rainfall or streamflow records in the vicinity.

One characteristic of streams in semi-arid areas, which has a significant bearing on their use, is that they are commonly 'influent'. This means that they are discharging to groundwater through the stream bed, with the result that the quantity of flow diminishes noticeably downstream. This influent discharge is usually confined to the riparian zone which sustains a much denser vegetative cover. Thus, care must be taken in extrapolating streamflow measurements from one point to another, especially in the drier zones.

On the other hand, a stream may become 'effluent' as it crosses from a recharge to a discharge area, and springs in the bed or along the banks are usually reflected in more luxuriant vegetation, which can be easily picked out in aerial surveys or in colour imagery.

4.1.3 Rivers

An occasional feature of pastoral lands is the existence of large perennial rivers which originate in higher, more humid regions. Seasonal variations in discharge are determined by the rainfall distribution in the humid parts of the catchment and by the geological controls on baseflow. Dry-season flow, therefore, may be sufficient for the constant abstraction of water for livestock needs.

A characteristic feature of this type of river is the high sediment load it carries. This poses special problems at the site for abstraction, since any structure or diversion which causes a decrease in velocity in the river will cause deposition of sediment.

Such rivers are prone to change course during a flood, particularly if they are meandering over a wide, flat plain. It is not uncommon for pump houses, diversion weirs, bridges or other riverside structures to be either destroyed or left abandoned by a sudden change in course. Balancing reservoirs or barrages can assist with smoothing out the natural variations in flow, but their high cost is usually only justified for hydropower generation or multipurpose projects. However, livestock projects should take advantage of such schemes, since they afford a means of ensuring more reliable dry-season flows and more secure abstraction points.

Rivers originating wholly within range areas are rarely perennial and are always subject to the same problems of erratic seasonal flow. The wide range of discharge creates special problems in dealing with high floods, so that it is imperative that management schemes be introduced to lessen the magnitude of peak floods and to extend the duration of flow.

4.1.4 Lakes

Natural lakes may be permanent or seasonal, fresh or saline depending on their water balance and many other limnological factors which are beyond the scope of this report. High evaporation rates and low inflow will clearly lead to the concentration of dissolved chemicals, and water quality will usually be a critical factor in deciding whether lakes can be used as a resource for livestock watering or not.

Permanence is another feature which determines whether or not lakes can be used. Many lakes persist during a run of wet years and then dry up completely when a prolonged dry spell occurs. There is often an abrupt change in water level, because a return to a wetter period is usually heralded by unusually high rainfall. A good example of this occurred during the season 1961/62 when the majority of the East African Rift Valley lakes rose to high levels, often 5 m above the previous year's maximum.

These fluctuations, both annual and seasonal, are a consequence of variability in rainfall. Unprecedented high levels of major lakes such as Lakes Victoria, Tanganyika and Malawi, during the 1960s and 1970s, led to speculation about the effect of man on the hydrological cycle – particularly with respect to changes in land use and the construction of artificial controls on outflow. Intensive studies (WMO, 1974; Kidd, 1983), however, have not been able to detect any evidence of man having other than a minor effect. There is overwhelming evidence, on the other hand, that a run of wetter-than-average years, such as occurs from time to time in a random sequence, can produce exceptionally high lake levels.

A corollary to the occurrence of wet periods in random sequences is the more disturbing possibility of a return to the drought periods which have been experienced at different times, and in different areas, since the beginning of this century when most records begin. The economic and social consequences of such droughts have already been felt in the Sahelian zone of West Africa. Where natural lakes are shallow and clearly dependent upon annual recharge, caution should be exercised in placing too great a reliance on their permanency.

4.2 GROUNDWATER

4.2.1 The occurrence of groundwater

The general principles behind the occurrence of groundwater have been discussed in Chapter 3. Aquifers can be of many different types, with varying characteristics. The geology of the pastoral areas of Africa is also varied and complex. The majority of existing boreholes in tropical Africa have been drilled without hydrogeological advice, by drillers armed only with an intimate knowledge of local conditions and many years of experience.

At the same time, many of the older existing boreholes have been located in regions of favourable hydrogeology, particularly recharge, because groundwater development first took place in regions of high agricultural productivity. It becomes increasingly difficult to locate sites as the recharge potential diminishes. Nowadays, there is a need for greater professional input, and there are legal requirements to be met in the construction and completion of boreholes. It is increasingly important to take into account potential yield, water chemistry and sound design and completion, in order to minimise both the capital costs and the maintenance costs of a borehole.

Most groundwater or hydrogeology textbooks deal in depth with the subjects of groundwater geology and exploration for groundwater

(Todd, 1959; Davis and De Wiest, 1966; Freeze and Cherry, 1979). This section is intended only to give a brief background to the methods of exploiting groundwater resources. While the more expensive methods of exploitation (deep boreholes) should not be undertaken without the advice of a professional hydrogeologist, the less sophisticated methods (shallow wells and boreholes) can be applied often with a minimum knowledge of the hydrogeology of an area.

Freeze and Cherry (1979) summarise the main types of aquifers according to their geologic origin and their porosity. Dealing first with sedimentary rocks, the most abundant category is in fine-grained rocks such as shales, clays and siltstones. These make up about 50% of all sedimentary rocks, and are characterised by having relatively high porosities but low permeabilities. They are commonly barriers to the movement of water, although they provide storage for large quantities of water which cannot easily be extracted.

Sandstones form the next largest group and, depending on the degree of cementation and packing of the individual grains, they can have porosities of 5 to 30%. Permeabilities are also very variable and seem to be a function mainly of grain size and degree of cementation.

Limestones (including dolomite) are another major group of consolidated sediments. Once again the fine-grained structure of limestones (excluding limestone breccias) tends to produce medium to high porosities but low permeabilities. The major characteristic of limestone, however, is the importance of fractures and solution openings, which are common features and can yield large quantities of water.

Undoubtedly the most important sedimentary formations, from the point of view of groundwater yield, are the unconsolidated or non-indurated sedimentary deposits such as alluvium, loess, dune sand, marine sands and clays, colluvial deposites and lacustrine clays and sands. Porosities range from 20% in coarse, poorly sorted alluvium to about 90% in soft muds and dry organic material (Todd, 1959). Porosities of between 25 and 65% are most common. Permeability and specific yield are dependent upon the shape, packing, size distribution and incipient cementation or clay coating of particles. Such sediments occur in alluvial basins and coastal margins. They are readily identifiable and indicate where high-yielding aquifers are most likely to occur. An understanding of the geomorphology or palaeogeomorphology will often help to identify buried valleys or deltaic fans, where the coarsest sediments are likely to be found. Inland drainage basins (which are common in arid climates) and lakes are areas where slack-water deposits such as silts and clays abound. Careful reconstruction of recent geological history may provide the necessary clues to the subsurface geological conditions, so that the highest yielding sediments can be located and traced.

Igneous and metamorphic rocks are usually regarded as giving the most unfavourable geological conditions for the occurrence of groundwater. Precambrian basement complex rocks of this type cover large areas of tropical Africa. High-grade metamorphic rocks, often intensely folded and granitised, form the tectonic shield areas of the continent. They are impermeable in their fresh state with very low porosities (1 to 3%). Groundwater occurs in small fissures or fractures which are difficult to locate, and only where widespread faulting and fissuring has occurred will the yield be high enough for wells to be developed.

These rocks have been exposed to tropical weathering for millions of years, however, and the layer of unconsolidated material produced by *in situ* weathering forms a most important aquifer which has largely been ignored. Except where the weathered material has been stripped from the parent material by recent erosion or fluvial rejuvenation, or where rock resistant to erosion outcrops in erosion residuals, deep weathering produces a shallow aquifer, generally less than 30 m thick, which is of great importance as a source of rural water supply. This weathered zone will normally support a yield of 0.5 l/sec, which is adequate for a hand pump. Furthermore, provided that the areas where the bedrock is near the surface are avoided, such yields can be found over wide areas without the need for sophisticated siting techniques.

The exploitation of this aquifer has largely been neglected in the past, but recent work in Malawi (Chilton, 1983) has demonstrated its importance in rural areas. Boreholes drawing on this aquifer need only be 20 to 30 m deep, compared with 45 to 50 m in the past.

The final major group of rocks encountered in resource evaluation is the volcanic group. These have a very wide range of hydrogeological properties. Recent basalts may have very high transmissivities, whereas fine-grained tuffs or dikes usually have very low permeabilities. Vulcanicity is associated with the African Rift Valley and with tectonic plate movements on the eastern side of the continent. Here, the quaternary to recent volcanics form important aquifers, while the mesozoic volcanics have lower porosities and permeabilities. Boreholes in the mesozoic volcanics tend to be deep; the median value of boreholes in volcanic rocks in Kenya being 125 m (TAMS, 1979). Water chemistry of the deeper volcanic aquifers is frequently poor (for example in these Kenyan boreholes, high concentrations of fluoride are commonly encountered). The rapidly cooled surface basalt flows, on the other hand, yield high-quality water, often in large quantities.

4.2.2 Prospecting for groundwater

Surface geological methods of prospecting for groundwater have been mentioned already. Analysis of available geological information (maps, cross-sections), air photographs and, more recently, satellite imagery, all contribute to assessing the location of aquifers. Hydrological techniques help in assessing the recharge potential of such aquifers. This is often a good guide to potential water chemistry, since the 'fossil' waters, which are not being flushed with fresh water, are the most likely areas of non-potable water in zones of otherwise favourable geology.

Hydrobotanical studies from aerial photographs can also be instructive. Phreatophytes take their water from shallow sources; halophytes, together with white surface encrustations, indicate shallow, brackish or saline groundwater; and xerophytes are plants resistant to drought, suggesting a considerable depth to the water table. Care must be taken when using the presence of phreatophytes as an indication of recoverable groundwater. Plants are able to abstract water from impermeable, fine-grained materials which would not normally contribute water to a well or borehole.

Geophysical methods cover a range of techniques for interpreting the subsurface geology. They are usually much more expensive than geological or hydrological reconnaissance surveys, and are only used where the yield is important, or the economics of utilising groundwater justify the cost of locating the source. They range from simple electrical resistance traverses with different electrode configurations to seismic refraction techniques and magnetic and gravity surveys.

All geophysical methods have limitations where the subsurface geology is complex, and they are usually supplemented by the analysis of existing borehole records or the results of test drilling. Ideally, both drilling and geophysics should be used, but economic constraints dictate the extent to which subsurface methods can be used at all. Clearly, if any drilling takes place, careful logging with depth will yield valuable direct information. Once again, logging can range from simple lithological logging to electrical logging (spontaneous potential and resistivity) and radiation logging (gamma and neutron). Bailing tests will also give a coarse indication of yield with depth.

In the context of pastoral areas geophysical techniques will seldom be economic. However, comprehensive reconnaissance surveys, backed by local information on the location of springs and the depth and reliability of shallow wells, can often produce sufficient information for a preliminary drilling programme. As information accumulates from the logging of these first boreholes, so the picture of subsurface conditions will become clearer and the feasibility of a second phase can be assessed.

4.2.3 Characteristics of the groundwater of semi-arid regions

As the aridity of the climate increases, certain characteristic features appear which can have a dominating influence on the development of the groundwater resource. A general decrease in the volume of streamflow can often lead to the inability of a river to maintain its course over volcanic or tectonic obstructions (Todd, 1959). Enclosed drainage basins are common, therefore, filled with fine lacustrine deposits mixed with saline residues. Fresh water is usually found only on the margins of such basins, or in deeper lying aquifers which are not affected by the upward movement or surface concentration of salts in response to high evaporation rates. Recharge is commonly through channel bottoms or through the vegetated parts of isolated hills. Small recent volcanic features act as collecting catchments for rainfall, particularly where craters still exist.

In the African context, a knowledge of the geomorphology of arid regions will often prevent abortive efforts to locate groundwater in impermeable bedrock. The formation of pediments at the base of erosion residuals, and rock pavements where wind erosion is significant, should be borne in mind during the initial reconnaissance. Pediments are often covered with a thin mantle of colluvium which makes them resemble alluvial fans. Apparently dense, quasi-parallel drainage networks on extensive peneplains indicate impermeable bedrock near the surface, where both streamflows and slope are insufficient to cause concentration of flow into fewer, well defined channels. Rejuvenation of drainage systems by recent tectonic activity can also cause the stripping of the weathered mantle from basement rocks. All the above indications can be used to avoid areas of shallow bedrock where, even if fissures and fractures abound, storage and recharge are likely to be insufficient for even small human or animal communities.

Another feature of the semi-arid regions is the existence of large 'sand rivers'. Either high rates of geologic erosion or accelerated erosion produce large quantities of coarse material which have a potential for development.

Under natural conditions available water is limited, and this acts as a control on the degradation of forage within easy reach of the water course. This situation can be easily upset if artificial methods are introduced to prolong the availability of water. The balance is a delicate one, and development of permanent watering points can have a negative effect if forage availability and water supply are not considered together. With that factor in mind, the exploitation of the available resource can now be discussed, leaving the questions of forage and water needs, and the organisation and management of water supplies, to the companion reports in this series.

5. WATER QUALITY

5.1 INTRODUCTION

Although artificial pollution of natural water resources in tropical Africa is still comparatively rare, and limited to the vicinity of large urban centres and mining areas, the potable quality of water cannot be taken for granted, particularly since only a small percentage of the population has access to treated water. Pastoralists frequently share what water is available with their livestock and, although the latter have a higher tolerance to degree of contamination, water quality should always be considered as one of the limiting factors in developing a water resource.

The chemical, physical and biological characteristics of a water supply depend on many factors; for example, on the climatic, soil and geological conditions, and also on the activities of man within a drainage basin. The chapter discusses the main features concerning the natural quality of the resource and the ways in which sources can become contaminated by man's activities.

Whenever a potential water resource is being exploited, chemical and bacteriological analyses of water samples should be made as a standard measure. Not only does this give direct indications of the potability of the water, taking due account of possible seasonal effects, but it aids the future exploitation of the resource.

Chemical analyses are routinely performed by most public analysts and water laboratories. Analytical methods differ somewhat, but most of the field and laboratory procedures are essentially similar. Reference should be made to the standard procedures of the chosen laboratory and questions of non-standard requirements or additional analyses can then be discussed. Whereas samples for chemical analysis can easily be collected, stored and analysed retrospectively, samples for bacteriological analysis have to be carefully stored, refrigerated (chilled) and analysed within a short time of collection. Normally, the requirements for temperature control are that the sample is stored at or below 4°C to retard bacteriological decay. Analysis should preferably be carried out within 6 hours even when the above storage requirements are met. Otherwise, it must be accepted that the count of bacteria obtained will be lower than exists in the water source.

When collecting samples for chemical analysis, acidified and unacidified samples should be taken in order to preserve unstable cations, which may otherwise precipitate, and to prevent adsorption or plating onto the bottle surface.

To facilitate field reconnaissance surveys, portable test kits are available for measuring electrical conductivity, pH, major ions (CO_3^{2-}, HCO_3^-, Cl^-, SO_4^-, NO_3^-, Ca^{2+}, Mg^{2+}), total coliform and faecal coliform. The last of these is particularly important as an indicator of the presence of pathogens. It should be emphasised, however, that the presence of indicator organisms cannot be taken as a measure of the quantitative degree of faecal pollution or of the presence of pathogenic micro-organisms. If faecal contamination is indicated, then pathogens may also be present and professional advice should be sought.

5.2 HYDROCHEMICAL ASPECTS OF THE HYDROLOGICAL CYCLE

Chemically pure water does not exist in nature. Rain droplets form on hygroscopic nuclei – particles which have an affinity for water such as sodium chloride or sulphur trioxide – and these droplets have the ability to dissolve gases (such as carbon dioxide) from the atmosphere. Except in heavily industrialised areas, however, acidic rain is not a problem, and saline rainfall, although common in coastal zones and in arid continental areas where salt-laden dust is circulated in the atmosphere, still gives rise to relatively small concentrations of salt.

By far the most common source of the dissolved solids is in the passage of water through the soil and weathered mantle to bedrock. Chemical weathering causes the dissolution of minerals from rocks. The active agents are weak acids such as carbonic acid (formed by the dissolution of CO_2 especially in the root zone) and humic acids (formed by the biological decomposition of organic matter). Another source of dissolved solids may be the oxidation of minerals present in the soils and rocks. Salts are added to infiltrating water from the soluble products of soil weathering. Evaporation tends to concentrate these salts in and above the root zone, leading to high surface salinities in arid areas where leaching by rainwater is not effective in diluting the salt solutions. Similarly, poorly drained areas and certain confined aquifers are highly susceptible to high saline concentrations.

The presence of evaporites in sedimentary sequences also leads to the enrichment of groundwater, with the specific ionic species derived from these minerals, e.g. $CaSO_4$, NaCl.

As the depth of the aquifer increases, the rate of circulation of groundwater decreases. The greater retention times allow more minerals to be dissolved so that concentration tends to increase with depth. This can lead to a vertical stratification, with bicarbonates predominant in the upper zone and chlorides at depth. Evaporation from unconfined aquifers at the surface will tend to reverse this pattern in arid regions.

Because of the variety in which major ions can occur, it is sometimes convenient to group the common configurations into categories known as hydrochemical facies, and references may be found to such in hydrogeological texts. Hydrochemical facies can be defined as distinct zones which have anion and cation concentrations which can be described within certain composition categories (Freeze and Cherry, 1979). Thus, for example, one can refer to calcium-magnesium facies, calcium-sodium facies, sodium-calcium facies and sodium facies.

In stratified or mixed assemblages of unconsolidated sediments or rocks, groundwater can follow many different geochemical evolution paths, depending on the sequence of encounter, relative rates of mineral dissolution, mineral availability and solubility, presence of organic matter and bacteria, carbon dioxide conditions and temperature. In addition, a change in climate can cause a change in the rate of infiltration and leaching, or a change in the rate of evaporation. The chemical composition of groundwater, therefore, may well be a function of the palaeohydrogeology, in addition to the other variables. No attempt will be made to enter into the complex subject of genetic classification of groundwater in this report. Interested readers should refer to Freeze and Cherry (1979), Eriksson (1981), Schoeller (1977) and the numerous references contained in those texts.

5.3 MAJOR CHARACTERISTICS OF DIFFERENT TYPES OF RESOURCE

5.3.1 Surface water

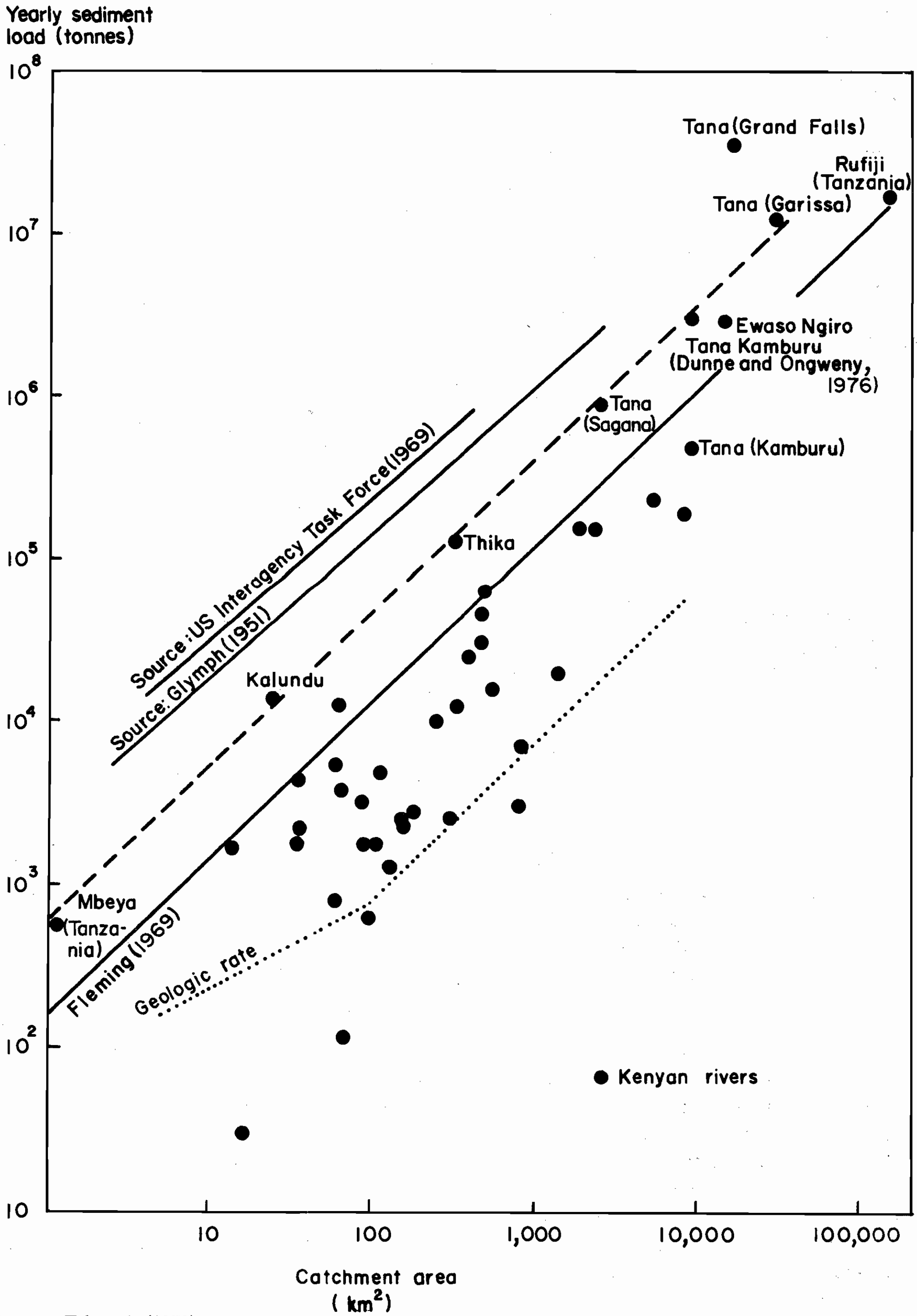
Because of the short time of travel of surface runoff compared to groundwater, and the frequent removal of available minerals from the soil surface, streams and rivers normally contain far lower concentrations of dissolved solids than does groundwater. Exceptions occur wherever groundwater discharges into surface streams and forms a major component of the flow. In volcanic areas highly mineralised springs, often of high temperature, can produce great changes in the chemical composition of streamflow over short distances. During times when baseflow predominates, the concentration of dissolved solids can also be expected to rise considerably.

Stormflow has the shortest time of travel, but high velocities enable the runoff to remove and transport large quantities of suspended solids. These consist of particles of rock material ranging in size from large boulders to very fine clay particles, together with varying amounts of organic material. The total sediment yield of a drainage basin depends on a large number of variables, often grouped under 'rainfall erosivity' and 'soil erodibility' (ASCE, 1977). Catchment size has an influence because the rate of sediment movement attenuates as particles move from the erosion source into larger drainage basins.

Accelerated soil erosion, resulting from overcultivation, overgrazing and deforestation, will increase the total sediment load in streams and rivers. Often this can be gauged by measuring the suspended solids at different flows, so that a sediment-discharge curve can be constructed. When combined with a flow-duration curve, it is possible to integrate the total suspended sediment yield for a year. Unfortunately, the most difficult part of the sediment load to measure – bed load – can be a significant proportion of the total sediment yield, particularly in semi-arid areas. Conventional estimates of 25% of total load can grossly underestimate bed load transport on steep catchments.

Figure 23 gives an indication of how sediment yield varies with catchment size (Edwards, 1979). The high yields recorded in the USA reflect the measurements from loess-covered catchments where easily erodible, fine particles abound. Crystalline rocks are better represented in the curve of Fleming (1969). Highly turbid water resulting from flash floods is usually organi-

Figure 23. *Suspended sediment yield in relation to catchment area.*



Source: Edwards (1979).

cally polluted, but high dilution rates often render it less of a threat than the low flows. Retention and storage will allow much of the suspended sediment to be deposited, but clay particles can remain in suspension for long periods, cutting down the penetration of ultraviolet, bacteria-killing sunlight.

Bacteria and other micro-organisms play a vital role in the self-purification ability of a river, because they biologically break down the organic matter present into simpler inorganic substances. In doing so, however, they exert an oxygen demand on the water. Where excessive quantities of organic matter are present, as for instance below the outfall of a sewage discharge, the increased bacterial activity can seriously deplete the oxygen content to below that which can sustain aquatic life (4 mg O_2/l). Where severe pollution occurs, the river can become devoid of oxygen and is termed anaerobic. Such rivers become foul smelling.

The biochemical oxygen demand (BOD) of a water body is a measure of the oxygen consumed by bacteria in breaking down organic material present in the water.

The standard test is conducted on samples incubated at 20°C for a period of 5 days (BOD_5). In hot climates the test requires a refrigerated incubator. A much simpler and more rapid test (completed in 2½ hours) is the determination of chemical oxygen demand (COD), which is a measure of the oxygen required to break down the organic material supplied by strong chemical oxidants.

Both tests – COD and BOD – measure the stress or 'load' a quantity of organic waste puts on a receiving water. Pollution load is the amount of dissolved oxygen that organic material will remove from water while being converted to carbon dioxide and water by micro-organisms. When wastewater contains only readily oxidisable organic material, and nothing that is toxic to bacteria, COD test results are a good estimate of BOD values.

5.3.2 Lakes and swamps

Natural retention of surface waters in lakes and swamps leads to a dramatic reduction in suspended solids. Swamps often filter finer particles from suspension reducing the turbidity. Against these beneficial effects, high evaporation and transpiration rates lead to a concentration of dissolved minerals and, under certain conditions, organic pollution can increase. It is generally considered that in most natural water bodies bacteriological concentrations are reduced as a result of the unfavourable bacteriological environment (see Powell, 1964). In turbid lakes and swamps, however, not only are bacteria adsorbed on the surface of suspended clay minerals but, given a supply of oxygen, a source of assimilable organic carbon and high temperatures, the natural decay of bacteria will be inhibited and, in this very favourable environment, bacteria will multiply rapidly.

Prolific algal growth is a common nuisance where dissolved nutrients are present (N, P). High concentrations of blue-green algae, notably *Microcystis* and *Anabaena* in water consumed by stock, have been reported as the cause of fatal poisoning in many instances (Gorham, 1964, Powell, 1964). In slow-moving waters vegetational pollution is a serious problem. The water hyacinth *(Eichornia crassipes)*, Kariba weed *(Salvinia molesta)* and parrot's-feather *(Myriophyllum aquaticum)* are among the species of aquatic weed which are found in tropical Africa. They are notorious for their spectacular capacity for explosive population growth. Some are native species and some, like the examples cited, have been introduced from South America. All have the capacity to reduce flow, to choke small lakes, to reduce oxygen levels and water quality and to provide breeding places for mosquitoes and for the snails which are the intermediate hosts of schistosomiasis.

5.3.3 Groundwater

Groundwater is generally free from suspended solids and objectionable colour but, as has been discussed above, it contains higher concentrations of dissolved solids than surface water in the same locality. Preliminary indications of total dissolved solids can be obtained from simple electrical conductivity (EC) tests made in the field. Chemically pure water is a poor electrical conductor whereas highly mineralised water is a very good conductor. EC, measured in microsiemens per centimetre, therefore, is a rapidly obtained measure of total dissolved solids. EC is normally 1.4 to 1.8 times the total dissolved solids concentration in mg/l, which implies that readings of 3000 microsiemens/cm will indicate a concentration in excess of the WHO recommended maximum levels (see below).

The pH of groundwater is also a rapidly obtained measure and indicates whether the water is acidic ($pH < 7$) or alkaline ($pH > 7$). Groundwater generally has a pH within the range 6 to 9. Acidic waters are 'aggressive' and lead to the solution of iron and manganese, both of which impart an unpleasant and unpalatable taste.

Where mineral deposits lie within the zone of circulating water, toxic minerals such as selenium, zinc, arsenic, lead, fluorides and nitrates may be taken into solution. Under natural conditions the mineralised zone may be surrounded by an aureole of contaminated water. Pumping from a nearby well or borehole can lead to water from the zone of contamination being drawn towards the abstraction point. As this type of mineralisation may not be obvious when water is first tested for chemical quality, there is merit in periodic resampling to monitor water chemistry changes, especially where there are indications of the presence of toxic minerals in the area.

Deep sedimentary basins in arid areas are often the source of fossil or connate water. These types of groundwater have little or no circulation and are usually of high salinity. Sedimentary deposits on the arid border between Kenya and Somalia contain fossil water with more than 10 000 mg/l of total dissolved solids. Mesozoic sandstones of North Africa, on the other hand, have fresh water which was stored during the Pleistocene epoch and are a good example of exploitable fossil water.

5.4 CONTAMINATION OF WATER RESOURCES

Contamination of water resources can occur naturally over very long periods of time, particularly in response to climatic change. But the major cause of contamination by far is man's activity and, in this case, contamination can occur rapidly and dramatically.

Surface waters can be choked with sediment as a result of accelerated soil erosion caused by destruction of protective vegetation. Noxious aquatic weeds, once introduced into a region, can be rapidly spread by birds, animals and humans.

Fortunately, the major sources of surface water pollution – urban and industrial effluent – are absent in the pastoral regions, but local concentrations of nitrates due to poor dilution of untreated organic waste are a hazard to livestock and humans (infantile cyanosis), particularly during the low-flow season. Nitrates are usually reduced in surface waters by denitrifying bacteria, but water containing large amounts of decaying organic material (e.g. manure) may be very high in nitrate ($<$ 200 mg NO_3/l) and so may constitute a potential danger.

Contaminated drinking water is a significant factor in the spread of infectious, water-related diseases. Lack of water for personal hygiene leads to the increased possibility of transmission of disease by a variety of faecal – oral routes. Both from a human and livestock point of view, reliance on polluted surface water supplies can lead to a high incidence of water-based diseases (bilharzia, river blindness, schistosomiasis, Guinea worm) and insect-vector, water-related diseases (trypanosomiasis, malaria, yellow fever, dengue and onchocerciasis). In considering the provision of additional water sources, therefore, their effect on the possible spread of disease must be taken into account.

Micro-organisms and spores of diseases common in livestock may also be present in water supplies. Prevention of contamination of livestock drinking water with urine, faeces and carcasses is especially important if the presence of a water-borne or water-associated livestock disease is suspected. Among bacterial infections, leptospirosis and salmonella are common and both affect humans. Table 10 lists a number of significant viral diseases which may be associated with stock drinking water (Australian Water Resources Council, 1974).

A number of livestock parasites, including protozoa, flatworms and roundworms, spend part of their life cycle in water. Faecal contamination is the usual means of introduction into the water.

It is recommended that the faecal coliform level should be used as an indicator of pathogenic organisms. The mean monthly faecal coliform count should be less than 1000/100 ml with a maximum in any single count of 5000/100 ml (Australian Water Resources Council, 1974).

Table 10. *Significant viral diseases which may be associated with stock drinking water.*

Picornavirus infections, including:
- Foot-and-mouth disease
- Teschen/Talfan disease
- Avian encephalomyelitis
- Encephalomyocarditis
- Swine vesicular disease

Parvovirus infections

Adenovirus infections, including infectious canine hepatitis

Rinderpest virus

Swine fever (hog cholera)

African swine fever

Mucosal disease

Groundwater is normally of high bacteriological quality since the soil usually affords the underlying aquifer a considerable degree of protection against contamination. Local contamination of a groundwater source usually occurs if inadequate provision is made to prevent the ingress of polluted surface water around the borehole casing or well lining. If thorough attention is paid to grouting the casing or lining, and an adequate concrete apron is provided above ground, this common route of bacteriological contamination can be avoided. Shallow wells are more susceptible to lateral movement of contaminated water from sources of organic pollution such as pit latrines, particularly in areas of high water tables. In consolidated porous soils, 2 to 3 m of vertical separation between latrine bases and the water table and 50 m of lateral separation are normally sufficient to prevent gross pollution of shallow wells from pit latrines or livestock pens. In areas of high permeability or where the soils overlie fractured rock, however, the lateral separation may have to be increased to 100 m or more.

Cattle dips using arsenical acaricides are also a potential source of contamination, particularly since they are normally sited very close to a water source. Separation of the dip from the borehole or a change to more biodegradable, organophosphorus compounds are measures to be strongly recommended.

Mention has already been made of the possibility of drawing in contaminated water from mineralised aureoles during pumping. Care must also be taken in the presence of saline aquifers not to overpump a borehole, thus causing intrusion of the highly mineralised water into the fresh aquifer. This problem commonly arises in coastal aquifers, but in general only motorised boreholes will be capable of drawing off sufficient water to cause saline intrusions.

5.5 TOLERANCE LIMITS FOR HUMANS AND LIVESTOCK

Within certain limits, the presence of minerals in drinking water is beneficial. In arid regions body electrolytes can be rapidly depleted by perspiration, and a constant intake of salts is required.

Drinking water standards for livestock may be less stringent than those for humans. Where a single water source serves both, the tolerance levels of the human body are obviously most important. The standards set by international bodies such as the WHO are extremely conservative and designed more for western industrialised nations where treatment of water is the norm. In tropical developing countries, not only are the bacteriological standards recommended by WHO almost impossible to attain in untreated drinking water supplies serving rural areas, but they also occasionally act in a negative way. Overzealous health officials may condemn a mildly contaminated water point as unfit to drink because, say, it contains 50 faecal coliforms per 100 ml and, thus, force the consumer to use alternative traditional sources, possibly containing 1000 or more per 100 ml.

Table 11 gives the WHO recommended standards for drinking water as laid down for Europe in 1971 and the rest of the world in 1972. Table 12 lists trace element and compound standards according to three categories of limits: recommended, mandatory and unofficial. Schoeller acknowledges that these standards cannot be universally applied, particularly with regard to the major anions and cations and total dissolved solids. Acceptable upper limits will depend on the climate, the total dietary intake and the work being done by the user. If no other water is available, the body adjusts to high levels of salinity. Cases have been recorded in South Australia of families living for several months on water having total salinity in excess of 5000 mg/l (Ward, 1946).

Table 13 gives the standards for drinking water in arid regions suggested by Schoeller (1977). These are based on the physiological tolerance of the user and the acceptability of the water as regards taste. Schoeller points out that it is the element with the highest value in relation to the limits which defines the water's suitability, rather than the value of the total dissolved solids.

Recommended concentration limits for livestock according to different authorities are given in Tables 14 and 15. There are differences between the values given by the agencies, but they serve as useful guidelines when developing new sources. It is clear that tolerance to total dissolved solids varies widely, and very high concentrations are acceptable in very hot, dry climates, or for short periods of time.

Bacteriological standards for animals are difficult to assess because of the varying degree of immunity to certain infections or parasitic diseases which indigenous livestock may possess. Limits for parasites and pathogens must be based on epidemiological evidence obtained from specific localities. A discussion of this topic is outside the scope of this report. It must be emphasised, however, that faecal pollution of water supplies by animals is potentially pathogenic to humans as well, and that the interaction between human and livestock populations using the same water source can produce harmful effects.

Table 11. *World Health Organisation and international water quality standards.*

	European standards	International standards
Biology[a]		
Coliform bacteria	Nil	Nil
Escherichia coli	Nil	Nil
Streptococcus faecalis	Nil	Nil
Clostridium perfringens	Nil	Nil
Virus	Less than 1 plaque-forming unit per litre per examination in 10 litres of water	
Microscopic organisms	Nil	
Radioactivity		
Overall α radioactivity	<3 pCi/l	<3 pCi/l
Overall β radioactivity	<30 pCi/l	<30 pCi/l
Chemical elements/compounds		
Pb	<0.1 mg/l	<0.1 mg/l
As	<0.05	<0.05
Se	<0.01	<0.01
Hexavalent Cr	<0.05	<0.05
Cd	<0.01	<0.01
Cyanides (in CN)	<0.05	<0.05
Ba	<1.00	<1.00

	European standards	International standards
Cyclic aromatic hydrocarbon	<0.20	
Total Hg	<0.01	<0.01
Phenol compounds (in phenol)	<0.001	<0.001–0.002
NO_3^- recommended	<50	
acceptable	50–100	
not recommended	>100	
Cu	<0.05	0.05–1.5
Total Fe	<0.1	0.10–1.0
Mn	<0.05	0.10–0.5
Zn	<5	5–15
Mg if SO_4 >250 mg/l	<30	<30
if SO_4 <250 mg/l	<125	<125
SO_4^{2-}	<250	250–400
H_2S	0.05	
Cl recommended	<200	
acceptable	<600	
NH_4^-	<0.05	
Total hardness	2–10 meq/l	2–100 meq/l
Ca	75–200 mg/l	75–200 mg/l

F In the case of fluorine the limits depend upon air temperature:

Mean annual maximum day-time temperature (°C)	Lower limit (mg/l)	Optimum (mg/l)	Upper limit (mg/l)	Unsuitable (mg/l)
10–12	0.9	1.2	1.7	2.4
12.1–14.6	0.8	1.1	1.5	2.2
14.7–17.6	0.8	1.0	1.3	2.0
17.7–21.4	0.7	0.9	1.2	1.8
21.5–26.2	0.7	0.8	1.0	1.6
26.3–32.6	0.6	0.7	0.8	1.4

[a] No 100 ml sample to contain *E. coli* or more than 10 coliforms.

Source: Schoeller (1977).

Table 12. *Water quality criteria for trace elements and compounds.*

Element/ compound	Comment	Recommended limit (mg/l)	Mandatory limit (mg/l)	Unofficial limit (mg/l)
Alkyl benzine sulphonate (ABS)		0.5		
Arsenic (As)	Serious cumulative systemic poison; 100 mg usually causes severe poisoning.	0.01	0.05	
Antimony (Sb)	Similar to As but less acute. Recommended limit 0.1 mg/l, routinely below 0.05 mg/l; over long periods below 0.01 mg/l.	0.05	0.05	
Barium (Ba)	Muscule (including heart) stimulant. Fatal dose is 550 – 600 mg as chloride.		1	
Beryllium (Be)	Poisonous in some of its salts in occupational exposure.			none
Bismuth (Bi)	A heavy mineral in the arsenic family – avoid in water supplies.			none
Boron (B)	Ingestion of large amounts can affect central nervous system.	1	5	1
Cadmium (Cd)	13–15 ppm in food has caused illness.		0.01	
Carbon chloroform extract (CCE)	At limit stated, organics in water are not considered a health hazard.	0.200		
Chloride (Cl^-)	Limit set for taste reasons.	250		
Chromium (hexavalent)	Limit provides a safety factor. Carcinogenic when inhaled.		0.05	
Cobalt (Co)	Beneficial in small amounts; about 7 μg/day.			none
Copper (Cu)	Body needs copper at a level of about 1 mg/day for adults; not a health hazard unless ingested in large amounts.	1.0		
Cyanide (CN^-)	Rapid fatal poison, but limit set provides safety factor of about 100.	0.01	0.20	
Fluoride (F^-)	Beneficial in small amounts; dose above 2250 mg can cause death.	0.7–1.2	1.4–2.4	
Iron (Fe)		0.3		
Lead (Pb)	Serious cumulative body poison.		0.05	
Manganese (Mn)		0.05		
Mercury (Hg)	Continued ingestion or large amounts can damage brain and central nervous system.			0.005
Molybdenum (Mo)	Necessary for plants and ruminants. Excessive intakes may be toxic to higher animals; acute or chronic effects not well known.			none
Nickel (Ni)	May cause dermatitis in sensitive people; doses of 30 – 73 mg of $NiSO_4.6H_2O$ have produced topic effects.			none
Nitrate (NO_3^-)	Excessive amounts can cause methemoglobinemia (blue baby) in infants.	45		
Radium (Ra-226)	A bone-seeking, internal alpha emitter that can destroy bone marrow.	3 pc/l		
Selenium (Se)	Toxic to both humans and animals in large amounts. Small amounts may be beneficial.		0.01	
Silver (Ag)	Can produce irreversible, adverse cosmetic changes.		0.05	

Table 12. Continued.

Element/ compound	Comment	Recommended limit (mg/l)	Mandatory limit (mg/l)	Unofficial limit (mg/l)
Sodium (Na)	A beneficial and needed body element, but can be harmful to people with certain diseases.			200
Strontium-90	A bone-seeking internal beta emitter.	10 pc/l		
Sulphate (SO_4^{2-})		250		
Zinc (Zn)	Beneficial in that a child needs 0.3 mg/kg/day; 675–2280 mg/l may be an emetic.		5	

Source: Schoeller (1977).

Table 13. *Water quality standards for arid regions.*

	Suitability for permanent supply			
	good	fair	moderate	poor
Colour	colourless	colourless		
Turbidity	clear	clear		
Odour	odourless	hardly perceptible	slight	slight
Taste at 20°C	none	perceptible	pronounced	unpleasant
Total dissolved solids (mg/l)	0–500	500–1000	1000–2000	2000–4000
EC (μS/cm)	0–800	800–1600	1600–3200	3200–6400
Na (mg/l)	0–115	115–230	230–460	460–920
Mg (mg/l)	0–30	30–60	60–120	60–120
$\left\lvert \frac{Mg}{12} + \frac{Ca}{20} \right\rvert$ meg/l	0–5	5–10	10–20	20–40
Cl (mg/l)	0–180	180–360	360–710	710–1420
SO_4 (mg/l)	0–150	150–290	290–580	580–1150

Source: Schoeller (1977).

Table 14. *Recommended mineral concentration limits for livestock.*

Element	Derived maximum working level (mg/l)	Element	Derived maximum working level (mg/l)
Arsenic (as As)	1.0	Lead (as Pb)	0.5
Boron (as B)		Magnesium (as Mg)	250 to 500
Cadmium (as Cd)	0.01	Mercury (as Hg)	0.002
Calcium (as Ca)	1000	Molybdenum (as Mo)	0.01
Chromium (as Cr)	1 to 5	Nitrogen (as NO_3^-)	90 to 200
Copper (as Cu)	0.5 to 2.0	Selenium (as Se)	0.02
Fluoride (as F)	2	Sulphur (as SO_4^{2-})	1000
Iron (as Fe)	10	Zinc (as Zn)	20

Livestock	Maximum total dissolved salts		Maximum magnesium
	Western Australia	Victoria	Australia
Poultry	2900	3500	
Pigs	4300	4500	
Horses	6400	6000	250
Dairy cows	7100	6000	250
Beef cattle	10 000	7000	400
Sheep on dry feed	13 000	14 000	500
Ewes with lambs	10 000	4500	250
Ewes in milk	10 000	6000	

Table 15. *Key water quality criteria for livestock.*

Substance	Upper limit	Substance	Upper limit
Total dissolved salts (mg/l)	10 000[a]	**Hazardous trace elements** (mg/l)	
		As	0.05
Radionuclides (pCi/l)		Cd	0.01
^{90}Sc	10	Cr	0.05
^{255}Ra	3	F	2.40
Activity	1000	Pb	0.05
		Se	0.01
Chemicals (mg/l)			
$MgSO_4$	2050		
NaCl	2000	**Organic substances**	
SO_4^{2-}	1000	Algae (water bloom)	–[b]

[a] Depending upon animal species and ionic composition of the water.

[b] Avoid abnormally heavy growth of blue-green algae. Parasites and pathogens conform to epidemiological evidence.

6. EXPLOITATION

6.1 GENERAL

The exploitation of an available water resource must always be closely linked to the ecology of the available pasture and to its actual or potential carrying capacity in terms of human and livestock units. Overdevelopment is not only wasteful of scarce resources, but it also carries the potential danger that, by attracting increased numbers of livestock without adequate control, the available forage is overutilised to its eventual destruction. This applies particularly to the fragile ecology of arid and semi-arid zones.

Under higher rainfall conditions with more abundant vegetation, overdevelopment in providing a more-than-adequate water supply is not so serious, and may indeed be desirable if one bears in mind that good range management can increase the carrying capacity significantly. A concomitant increase in the human population will lead to the establishment of new settlements and their infrastructure, creating a water demand which can often be met from the initial installation.

The simplest form of water exploitation is to water stock at the river bank or lake shore. All other forms of water exploitation require the use of technology which must be appropriate to the local conditions. Whatever its nature, an installation must be technically sound and reliable in operation; its capital and operating costs must be commensurate with the benefits it provides; and it must be capable of operating continuously with maintenance services which can largely be provided locally without undue reliance on assistance from a remote base.

While the criterion of sound engineering is readily understood, the other two criteria merit explanation. In the livestock industry, the inputs of development such as fencing, dips, skilled supervision and not least water, all require cost inputs which must be related to the outputs i.e. more and better animals and animal products. If the inputs exceed the outputs, the undertaking is not viable and, unless it is accepted as a social need to develop a particular livestock area, the project should not start. If the social need dictates the establishment of a project, then an element of subsidy must be built into the financing programme from the beginning.

The cost of water sufficient to sustain an animal for 1 year can be calculated from the designed capital cost and the estimated annual cost of operating the supply. This is very often a crucial factor in the economics of the entire undertaking. While economies can be achieved in such items as fencing, e.g. by using natural boundaries and supervising stock movement from paddock to paddock more closely, there are distinct limits below which economies in the cost of a water supply result in poor performance and unreliability.

The cost of operating and maintaining a supply is an item of vital importance, and yet it is overlooked or ignored all too frequently when capital development for all types of water supply is being planned. All water supplies require some maintenance; even a small earth dam, from which the stock are allowed to drink direct, needs care to ensure that the wall is not trampled and eroded by uncontrolled animals, and that the spillway is kept clear and safe from erosion. If cattle troughs are provided downstream, the control valves must be checked and cleaned periodically.

Skilled maintenance is required when machinery is used to extract and convey water to cattle troughs. Pumps and engines wear out and require a supply of spare parts, in addition to the daily amount of fuel and lubricants.

Such spare parts must be readily available, either on the project or from a local supplier.

Skilled staff are needed to carry out repairs and to fit replacements. The pump attendant has to be taught how to look after the machinery in his charge and must be closely supervised to ensure that he does his duty. If skilled mechanics are not available within reasonable distance of the installation, it will be necessary to employ such a man on the spot. The timely delivery of fuel is also a very important organisational aspect. All these items cost money, which must be provided for in the annual budget if the supply is to function reliably and contribute to the welfare of the animals and their owners. Wherever possible, the design of an installation must be suited to the local conditions as they affect operation, and this is particularly true for the remoter range areas where communications are poor or lacking and the technical ability of the people is low. If there is no simple alternative to a deep borehole with a costly pumping unit, for example, then adequate technical skill, spare parts and tools must be included in the overall plan and in the annual budget.

The choice of groundwater as a source for watering livestock is governed by the physical factors of its availability; by its location in relation to surface water sources; and by its quality and quantity. Economics also play an important role in decision-making since groundwater requires energy to bring it to the surface, in addition to that needed for distribution.

Despite this there are many situations where, because of propinquity and ease of access, groundwater is preferable to surface water, which may have to be piped or carried from a distant source. In many parts of the arid and semi-arid zones permanent sources of surface water do not exist, and groundwater then becomes the sole means of supplying herds and flocks.

The traditional grazing lands of tropical East Africa, for example, are characterised by the availability of forage and water, and their extent can be seen from a map of livestock populations, such as that in King (1983). Within these lands, many areas are underused because the natural supply of water does not match the forage potential. Others are overexploited or overgrazed because of the abundance of uncontrolled water supplies. It is these latter areas which are vulnerable to increasing desertification. As far as water is concerned, therefore, the task of range management is to apply controls in those areas where water is abundant. Such controls should be aimed at reducing the stock population to the carrying capacity of the pasture reserve, improving the quality of the animals produced and developing new areas of good forage potential. By providing additional water sources, areas can be used which are at present underused or not used at all. Such water sources should be strategically located and capable of effective management to ensure that the risks of overgrazing which occur in the natural state are minimised as far as possible.

Boreholes and wells equipped with pumping units are of special value as controls both in the grazing blocks and along stock routes, because they can be easily closed down simply by removing part of the equipment or by delaying delivery of fuel at times when the pasture has to be husbanded or fully rested for a period.

Careful planning is required, whether it be for the improvement of existing grazing areas, for the development of extensions or for totally new ranching blocks. Planning should be based on an assessment of the water resources, both surface and underground, and a review or a fresh survey of the range potential. This requires a knowledge of the potential water resources.

While surface water resources can often be assessed with relative ease, the identification of groundwater resources requires careful hydrogeological surveys to indicate favourable areas for development. Before a source can be positively included in the overall plan, wells need to be sunk or drilled and water test pumped.

Groundwater surveys should, therefore, precede the completion of the final plan for grazing blocks and cattle movement in the rotational pattern. This will avoid the mistakes that have occurred in the past due to plans for forage utilisation being based merely on assumptions of groundwater availability. When the groundwater survey has indicated that water is either inadequate or is to be found elsewhere, substantial revisions of block boundaries and grazing plans have resulted.

While this risk is not great in areas of sedimentary formations with a continuous aquifer, it is very real in those parts of the arid and semi-arid zones which are underlain by crystalline rocks of the Precambrian, or by Tertiary or older volcanics with discontinuous aquifers.

6.2 SURFACE WATER CONSERVATION

Excepting those narrow zones which are watered by perennial rivers, or permanent lakes and swamps which are the final recipients of catchment runoff, almost the entire tropical region is subject to periodic droughts of varying severity (see Table 16). Throughout the region there is a need to conserve the seasonal overland flow to

Table 16. *Summary of main areas with known large percentage of less than normal annual rainfall.*

	1968	1969	1970	1971	1972	1973
a. 12°–20° N						
Mauritania	whole country	extreme east	whole country	whole country	whole country	whole country
Senegal	whole country		whole country except south	west and north	whole country	whole country
Gambia	whole country		whole country	west	whole country	whole country
Mali	north and west; extreme southeast	north	whole country except northeast	whole country	whole country	whole country
Niger	far west and south	whole country except far south	whole country	whole country	whole country	whole country
Chad	whole centre region	whole country except far south	northwest	whole country	whole country except south	whole country
Sudan	whole northern region	northeast	east of centre	whole country except southeast	whole country	whole country except far south
Ethiopia		northeast and east	entire northern region	far north and east	almost countrywide	far north and southeast
b. 5°–12° N						whole country
Guinea-Bissau	whole country				whole country	whole country
Guinea				far north	far north	whole country
Upper Volta	extreme northeast		whole country	extreme northwest	north	extreme north
Ghana	far north		far north			—[a]
Nigeria	north		far north	far north	far north	—
United Rep. of Cameroon	extreme north-eastern region				extreme north-eastern region	

Table 16. Continued

	1968	1969	1970	1971	1972	1973
c. 5°–10° S						
Gabon				west	west and northeast	
Congo				southwest	southwest and northeast	
Zaire				whole eastern region		
Kenya		far south	far north	except northwest and southeast regions		east
United Rep. of Tanzania		large area in centre		extreme north-eastern region		extreme east
d. 10°–25° S						
Angola						east
Zambia			south		southeast	
Malawi		north				south
Namibia	extreme south-western region	east	whole country	far south	far south	south
Botswana	extreme eastern region	whole western region	whole country except southeast	whole country		
Southern Rhodesia	whole country		whole country	northwest		
Mozambique	part of centre		whole country	part of centre		
Madagascar	extreme western part of centre	far west	southwest			extreme north-western region
e. South of 25° S						
South Africa		northwest and far south	north	far west	west	

No entry = no evidence of serious dry period [a] = information not available Source: United Nations (1976).

ensure continuous water availability. This is especially so in the semi-arid and arid zones, where even in 'normal' years substantial runoff for short periods is followed by much longer periods of complete drought. In the humid and highland zones periods when no runoff occurs and when the flow in streams ceases or diminishes are shorter, but conservation measures to hold back the water and thus even out the flow pattern are still necessary for optimum water development and exploitation.

Good water conservation depends on good soil conservation, and the two are inseparable. Soil is conserved naturally by vegetation but, where this is disturbed by bad farming practices or by overgrazing, runoff will be intensified and there will be less recharge to soil moisture storage which sustains the vegetation. Intensified runoff erodes the soil and destroys its structure so that during the dry periods more soil is removed by wind. Successive runoff periods cause sheet and gully erosion even on gently sloping ground. Surface sealing leads to increasing velocities and the runoff periods become shorter but more intense, a process which leads to accelerated desertification.

If the soil cannot be conserved by natural means, artificial methods must be applied. In the more humid areas these may comprise trash lines on cultivated ground, earth embankments and terraces, and even stone walls. In the range areas of the semi-arid zone, a cheap method is the establishment of contour strips of natural vegetation (bushes and grasses which are not grazed), which will do much to retard the runoff and sustain the usable pasture. Badly degraded areas may require more extensive soil conservation schemes before surface water can be used as a resource. Although these are costly, it cannot be overemphasised that investment in the surface water conservation techniques outlined below will be wasted if due regard is not paid to reducing the velocities of surface runoff and the rate of soil removal.

6.2.1 Protection of springs

A spring is a concentrated discharge of groundwater appearing at the ground surface as a current of flowing water. To be distinguished from springs are seepage areas which indicate a slower movement of groundwater to the surface.

The quantity of water from a spring can be substantially increased by digging out the area around the spring down to an impervious layer, to remove silt, decomposed rock and other rock fragments, and mineral matter sometimes deposited by the emerging groundwater. In doing this particular care should be taken, especially in fissured limestone areas, to avoid disturbing underground formations to the extent that the spring is deflected in another direction or into other fissures.

The essential techniques for protecting a spring are as follows:

i) preventing overland flow from contaminating the source by digging a drainage ditch above the spring to divert surface runoff;
ii) constructing a simple collecting structure or reservoir around the spring to increase its yield during the day; and
iii) providing an outlet pipe to a discharge point or cattle trough to prevent contamination or destruction of the reservoir.

Since the major use of any watering point is during the day, constructing a reservoir will allow the spring to recharge the water consumed, enabling the maximum use of even quite small springs.

6.2.2 Rainfall harvesting

Rainfall harvesting is the term given to the conservation and storage of rainfall on outcrops and sheets of bare rock. In many parts of the tropical pastoral regions there exist inselbergs of granite or granitoid gneiss, which stand out prominently from the surrounding peneplains and receive additional precipitation from orographic rainfall, dew and mist. By encircling such rocks with a low masonry wall the runoff from the rock catchment can be guided into a storage area, which may be a natural fold in the rock blocked off with a concrete wall or, if such is not present, a tank excavated at the base of the rock. Sixty-three rock catchments and storage tanks were successfully constructed in Kenya between 1945 and 1962 as part of the surface water conservation programme of the Ministry of Agriculture (Min. of Agric., 1962).

The soil at such rock bases is usually very sandy and permeable. It is then necessary to line the excavation with masonry, concrete or brickwork, or with an impervious membrane such as sheet of butyl rubber or polythene. To prevent evaporation, pillow tanks of butyl rubber (which are made in capacities of up to 4500 m^3) have proved very effective in Kenya and their cost is generally below that of concrete or masonry work. Even in the arid zone with an annual rainfall of less than 250 mm more water runs off the rock during a short storm of shower than can be effectively and economically trapped and stored.

Disturbed and fissured rock outcrops with numerous pockets of vegetation, while still receiving the same volume of precipitation, would not normally be considered for development because of the additional high cost of bush clearing and sealing cracks and fissures. Their potential yield of water for stock is lost to deep infiltration and to evapotranspiration.

Often the catchment needs modification, usually by making the soil surface more impermeable to increase the amount of runoff. There are several methods available e.g. land alteration, chemical treatment and soil covers. Currently rainfall harvesting is for small-scale use, for farms, villages and livestock. Because rainwater harvesting depends on natural rainfall, the system will fail in drought years unless there is adequate storage. A rainfall-harvesting system once installed, however, will provide water without requiring fuel or power.

Under favourable conditions land alteration methods are the least expensive of all. Arid developing countries that produce and refine crude oil could use asphalt to construct harvesting catchments. Heavy petroleum fractions such as asphalt have limited demand and are often persistent pollutants, difficult to dispose of. Chemical treatments and soil covers, though still mainly experimental, are used worldwide on a modest scale. Although such treatments are technically feasible and successful, they are not yet economically attractive enough to generate widespread adoption (National Academy of Sciences, 1974; Wenner, 1973; FAO 1976).

No method of rainwater harvesting has been subjected to a long-term economic analysis. Large field trials in different areas are needed to build up a data base that could lead to a better understanding of the economic viability of alternative methods in varying economic environments. The major technical need is to reduce costs of sealing catchment soils and to make the treatment practical for a wider variety of soils and situations.

In applying water-harvesting methods to a given area, care is needed to minimise side effects. Poorly designed or poorly managed rainwater harvesting can lead to soil erosion, soil instability and local floods. Soil erosion, a constant concern, can be controlled if the slope is short and not too steep (and if land drains are suitably sloped). Slope also affects the quality and quantity of runoff. The most efficient water harvest is from small, gently sloping (preferably 1 to 5%) catchments.

6.2.3 Water spreading

One of the simplest techniques of using surface water for forage production and livestock water supplies is to take off streamflow from a suitable site by means of a diversion weir or an abstraction ditch and to spread it over the flood plain with a series of bunds, the last one leading into a small-stock watering dam or waterhole. It is to be stressed that such systems are difficult to maintain in remote areas of Africa and, if once allowed to deteriorate, may cause more damage to the land than if they had not been built. By retarding run-off more water is retained in the soil, and surplus flowing water is relatively silt-free.

Figure 24 gives two examples of layouts for water spreading (Pratt and Gwynne, 1967). In both examples a diversion furrow is set to take a proportion of stormflow from a river, and to guide this water far enough from the river to allow free flooding. This should only take place, of course, if the gradients on the flooded area are gentle enough to prevent erosion.

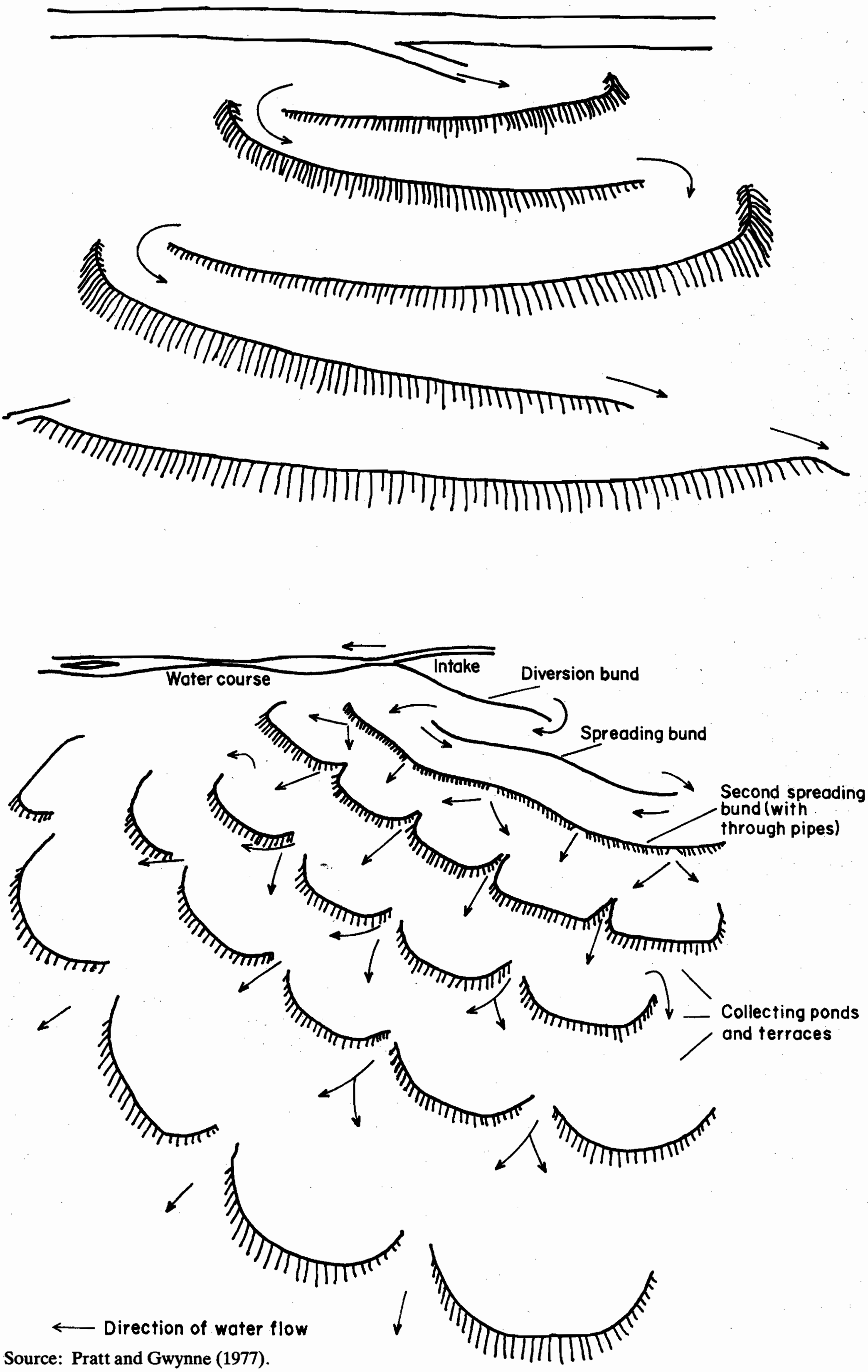
A disadvantage of this type of scheme is that the main offtake and diversion bunds can rarely deal with the exceptional flood. If such a flood occurs, widespread damage may ensue which will require repairing before the next flood comes. A succession of high floods may cause such widespread damage that the scheme becomes unacceptable to pastoralists who, in any case, may be reluctant to accept this type of sedentary commitment.

6.2.4 Tanks and *hafirs*

In addition to rainfall harvesting, water also has to be stored at or near points of use such as the centre of a grazing paddock or block or at temporary settlements and villages. Such storages do not normally exceed 90 m^3 in capacity, while a capacity of 45 m^3 is more common. Storage is necessary to ensure at least a 2 days' supply in the event of a mechanical breakdown interrupting the flow from the source.

A good form of storage, much used in East Africa and elsewhere, is the van Meerten tank, which is a circular reservoir of blockwork having a capacity of 45 m^3. It is built integrally with a circumferential cattle trough into which flow is controlled by a ball valve housed in a small chamber. A short pipeline serves a number of stand pipes for use by humans (Ministry of Agriculture, 1962).

Figure 24. *Examples of layouts for water spreading.*



Source: Pratt and Gwynne (1977).

Other types of diurnal storage are tanks made of corrugated, galvanised iron sheets or steel panels, circular butyl tanks held in a metal framework, or simply excavations in the ground. The latter, provided they are watertight and sited on a slope sufficient to permit a draw-off pipe to be connected to the base and taken out in a trench, are simple to construct and relatively cheap.

In a flat terrain, where drainage ways are absent or nearly so, it is still possible to conserve and store the runoff by excavating reservoirs, which have a variety of names. They are frequently referred to as 'tanks' but are also known, for instance, as *hafirs* in Arabia and East African countries, and *chacos* in the Americas. Figure 25 gives an example of a rectangular tank, many of which were constructed in East Africa using communal labour (Ministry of Agriculture, 1962).

If dug by hand, such reservoirs are usually rectangular in shape, but it has been found that an elliptical shape will make the most efficient use of earthmoving equipment. Runoff is guided into one end of the tank, with appropriate anti-erosion measures to protect the steep entry slope, while the other end is suitably graded, protected, and used as a cattle ramp down to the water. The spoil removed from the excavation should be carefully placed on two or preferably three sides of the reservoir, to form an embankment which will act as a windbreak to reduce evaporation losses and to prevent uncontrolled entry of animals. Locally adaptable trees such as *Commiphora, Euphorbia* or other thorny shrubs, planted on the outside of the banks, will protect them from wandering animals and will form an additional windbreak.

Haphazard dumping of the excavated soil at some distance from the excavation, rather than placing it to form an embankment, should be discouraged because it then becomes more difficult to control thirsty animals and to prevent premature silting-up of the storage.

Runoff is guided into the tank by means of feed furrows extending outwards more or less along the contour, but at a gently rising gradient. The length of such furrows may be 1 km or more to embrace a sufficiently large catchment area. This area is determined by the potential available runoff in relation to the seasonal rainfall. The furrow gradient will vary with soil type, and should be such that the furrow will neither scour nor silt up too rapidly. Some silting in the furrow is preferable to scour, which carries undesirable silt into the tank. In sandy, loamy soils a gradient of 1 in 600 has been found suitable. It can be a little steeper in clay soils.

The furrow can be dug by hand or by light machinery such as a tractor-towed terracer or grader. It will be a shallow 'V'-shaped cut, with soil packed as a low bank on the downhill side. Such furrows are a good aid in soil conservation, as they act as a trap for grass seeds which germinate and help to bind the soil. When the furrow silts up after several seasons, and is well grassed, it should not be dug out but a new furrow should be made just above it.

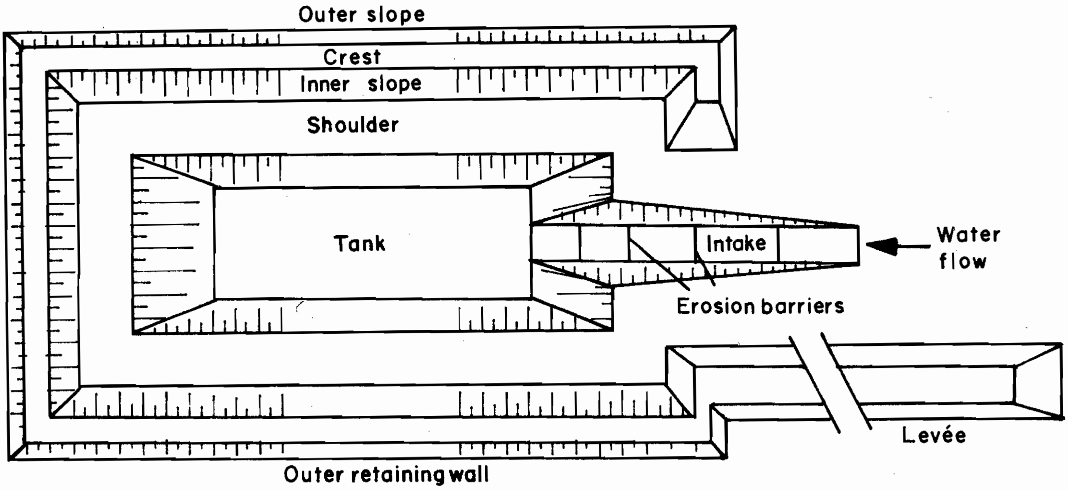
The idea of a so-called 'disposable' pond or tank, i.e. a pond with no provisions for reducing the silting-up, has been suggested. Such a pond acts as a silt trap and, when full, it indicates that livestock should be moved to another locality where water and forage are available. The advantage of such a policy is that after the pond has silted up, the surrounding vegetation can rest and recuperate from the intensive grazing which occurs around a watering point. However, the disadvantages of such a policy are several. First, it is destructive in terms of sites for small tanks or ponds, and good sites may not be abundant. Second, the lifetime of such a pond may be only one season or part of a season, making it difficult to integrate water supply into a grazing scheme. Third, because of the difficulty in predicting the life of such a water supply, it can only be regarded as a supplementary measure. A permanent water point within a grazing block must be included in the range management plan to provide water in periods of severe drought.

In the moister arid zone and in the humid zone, where water supplies for livestock are part of the domestic supply for settlements and centres of human population, stock should not be allowed to drink water directly from a dam or tank. With a dam, pollution of the water can be prevented by fencing off the dam area and conveying the water through the draw-off pipe to cattle troughs outside the perimeter. With a tank, the water must be lifted to the cattle troughs by a mechanical device such as an engine-driven pump, a windmill or a hand pump. Alternatively, a human watering point supplying satisfactory water can be constructed by digging a shallow well and connecting it to the tank by an infiltration gallery filled with graded sand and gravel (Figure 26). Since tanks are dug in impervious soil to avoid seepage loss, direct infiltration to a well through the natural soil will not be satisfactory.

6.2.5 Small dams

Perhaps the most common form of water conservation structure is a small earth dam across a

Figure 25. *Rectangular tank or hafir with dimensions for different capacities.*



	Dimensions for 3 capacities of tank		
	4.5 million litres	11.25 million litres	18 million litres
Length (m) top	60	85	100
bottom	30	55	75
Width (m) top	18	30	35
bottom	6	18	25
Depth (m)	6	6	6
Volume of excavation (10^3 m^3) = water stored (10^6 l)	3.9	11.0	17.0

For all sizes of tank, the recommended width of the shoulder between the tank and the outer retaining wall is 10 m; the length of the intake as illustrated is 60 m and its width 6 m. The levée can be any length.

Source: Pratt and Gwynne (1977).

drainage way which may have permanent or seasonal flow. 'Small' in this context is used to describe a structure no more than 3 m high which can be constructed without professional engineering advice. Given that suitable dam-building materials exist, the capacity of the dam will be determined by a combination of factors beginning with the topographical shape of the valley. A narrow, steep-sided valley allows the design of a short dam wall of considerable depth and a small surface area of open water which will be less susceptible to evaporation losses. A wide flat valley calls for a long wall, which may be costly, and which will result in a large surface area of open water and high evaporation.

The desired capacity is one which meets the needs throughout the dry period between rainy seasons, with allowance being made for evaporation loss. It will be larger in a region of unimodal rainfall – since the dry periods are longer – than in one of bimodal rainfall. The size of the dam will also be affected by the catchment area and the available runoff, which is estimated from the prevailing annual rainfall and runoff characteristics (see Chapter 3). This knowledge is also necessary to compute the design flood, which dictates the size and capacity of the spillway to discharge surplus water after the dam has filled. In the case of small dams where no loss of life is at risk if the dam fails, it probably will be uneconomic to design for a flood with a return period longer than 10 years. Larger structures require a higher safety factor and a detailed economic analysis to decide upon the return period of the design flood.

In the arid zone, where annual rainfall is often erratic and where there are wide variations from the mean, a dam may not fill in one season. But given 1 year of good rainfall, it has been

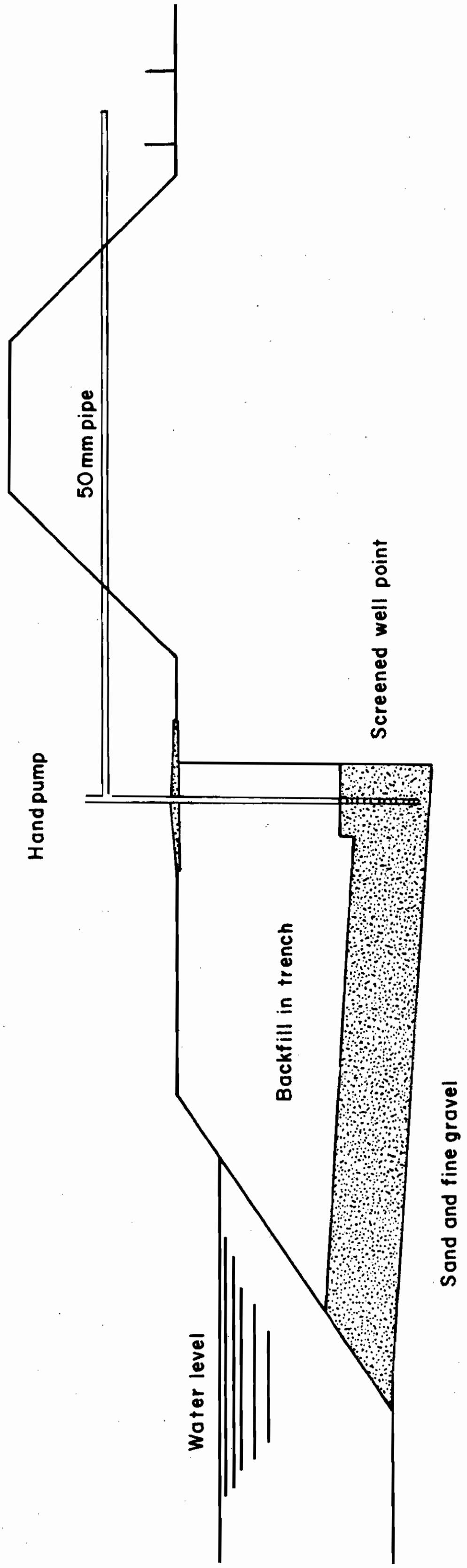


Figure 26. *Well point used for clean water supply from stock pond.*

found that such a dam is likely to fill and remain full thereafter.

In the humid zone and in the highlands, where rivers flow throughout the year but their volume of discharge may drop sharply during a dry period, regulatory storage dams, built to provide usable water and to maintain the river flow at the desired volume, must be fitted with draw-off pipes through the base of the wall which can be opened, to allow downstream users to receive their allotted share (compensation flow).

All dams should be protected by at least a minimum of soil conservation upstream of the wall to reduce the rate of siltation. The minimum would be a diversion ditch starting from a point upstream of the top water level in the dam and running around the impoundment on graded slopes, eventually leading the water back into the channel below the dam wall. Additional terracing above the ditch would also be desirable.

The apparent simplicity of small earth dams has led to countless attempts by enthusiastic, but ill-informed, would-be builders. The large proportion of failures has shown that care in construction and knowledge of the basic principles of siting, designing and building are essential.

What are the reasons for failure? The washing away or breaking down of a dam is more commonly due to overtopping and erosion of the embankments rather than to insufficient strength of the dam to support the weight of water. Continued erosion will lead to the breaching of the dam wall and, often, total collapse. Widespread devastation can be caused by the sudden release of large quantities of water.

Apart from overtopping, which is usually due to inadequate spillways, earth dams may fail due to:

i) undermining, caused by water flowing below the embankment with consequent collapse of the material above;
ii) enlargement of fissures, caused by shrinkage or by the use of wrongly chosen or badly compacted materials;
iii) percolation along tree roots, which were not properly cleared before construction commenced or which were allowed to grow later; or
iv) general weaknesses caused by percolation through the dam.

Excessive percolation through the dam wall may lead to a build-up of pore pressure in the earth matrix and consequent slip or slumping. This can also be accelerated by other causes such as ant and termite activity and the action of burrowing animals.

Other factors having an effect on the efficiency and life of a dam are as follows. If there is an inadequate catchment area above the site, it will not fill. If the soil is of a porous nature, the water will soak into the ground and empty the reservoir. If the dam is not well sited, the stream supplying it may change its course or cut itself another channel. If the stream flow contains much silt and proper silt traps are not constructed, the dam may become useless in a few years due to silting.

In the preparation for the construction of a small earth dam, the following guidelines are suggested:

i) In planning an earthen structure sufficient time should be spent in the investigation and comparison of possible sites, in the gauging of streams, in the compilation of meteorological data and in surveys of the catchment area. Some estimate should be made of the likely sediment movement in the catchment.

ii) For every structure it is necessary to know the geological conditions of the site. The choice of the structure and its location depends on the foundation conditions and the treatment required for safety and leakage. On no account should any dam over 3 m in height be constructed without qualified advice on these aspects. Rock foundations usually pose no problem except that they may require grouting. Alluvial foundations may or may not be consolidated, and rock-filled or clay cores may need to be constructed by excavating down to the solid rock.

iii) The type of dam, its selection and method of construction, largely depends on the availability of construction materials. When taking materials from the bed of a stream, upstream or downstream of the dam, care has to be taken to ensure that this has no adverse effect on seepage or on the stability of the dam.

iv) With a concrete or masonry dam, water may be allowed to spill over the crest of the dam and flow over the downstream face in time of floods. In an earthen structure such spilling must never be allowed. This is a fundamental rule of such structures.

v) Spillways should be cut out of solid ground, clear of the dam itself. The spillway channels should be continued downstream well away from the 'heel', or the downstream edge of the base of the dam, in order to prevent flood water which has passed over the spillway from eroding the dam itself.

vi) In building up the dam, the material must be spread in continuous shallow layers 10 to 15 cm deep over the whole area. It must be kept damp but not too wet. Each layer must be well compacted before the next layer is added.

vii) The calculation of spillway size is one of the controversial subjects in dam design, and different methods of flood discharge prediction are referred to in Chapter 3. The information necessary for designing the spillway should always include information from people living in the area under study.

The selection of a design for earth dams depends on the foundation conditions and the types and quantity of construction materials available. Several excellent reference books are available such as: *The design of small dams* (US. Dept. Interior, 1965) and *Manual of British water engineering practice. Vol. III* (IWE, 1969). A more project-oriented approach will be found in Ahmad (1977).

Whereas small earth dams can be constructed without professional advice, and are suitable projects for self-help or community participation, due regard must nevertheless be paid to safety both during and after construction. During construction an adequate diversion channel must be provided to carry the design flood. In the semi-arid regions, where a long dry season may allow enough time for the whole project to be completed within that season, this provision may be unnecessary. On the other hand, an untimely flood may carry away the whole of a partially completed earth dam.

Finally, there should be adequate inspection and maintenance facilities to prevent gradual erosion of spillways and embankments. If the slopes of the embankment are grassed to protect them from erosion by rainfall, livestock should if possible be prevented from grazing.

6.2.6 Reservoirs

A common design problem for all water supply systems is how to overcome the fluctuation in supply and demand. A stream which carried little or no water during the dry season can retain excess water from periods of high flow by means of storage or conservation reservoirs. The primary function of a reservoir, therefore, is to provide storage sufficient to meet the demand requirements. In the case of pastoral regions, demand for domestic and livestock purposes is not usually large compared to the storage capacity. The high evaporation losses from open-water surfaces (commonly 2 m or more per annum) and the percolation losses from simple earth dams, however, must be taken into account if the reservoir is to fulfil its role.

The storage capacity of a reservoir site is limited by topographical considerations and the height of the dam wall. Field surveys can provide data on the reservoir area in relation to the elevation of the water surface at the dam site, from which elevation-storage or capacity curves can be drawn.

If a choice of suitable dam sites is available, it is preferable to choose sites which minimise the surface area of the reservoir in relation to volume, as pointed out in the previous section. These will have steep-sided valleys which allow deeper water levels per increment of storage. Flat terrain makes it difficult to avoid large surface area to volume ratios and, where the cost of providing the water supply is high, it may be economic to consider methods for reducing the evaporative loss.

Demand is clearly related to the livestock population and the consumption by the pastoralists. Under certain circumstances the capacity of the reservoir may be limited to provide water only while there is ample forage. A reservoir can be used as a management tool, therefore, to maintain a balance between water supply and grazing potential.

Given the demand and the capacity of the reservoir, simple storage yield calculations can be made from a knowledge of streamflow and potential evaporation. It should be borne in mind that small reservoirs in the middle of hot, dry areas suffer from the 'oasis' effect. This is the increase of actual evaporation beyond the potential rate due to the addition of a large component of advective heat to the energy budget.

If records of streamflow are available over a sufficiently long period, cumulative streamflow minus evaporation and percolation losses can be plotted against time in a mass curve or Rippl diagram (Linsley and Franzini, 1964). Demand curves representing a uniform rate of demand are straight lines and can be plotted tangentially to a high point of a mass curve (i.e. when the reservoir is full). These represent the rate of withdrawal from the reservoir, and the maximum departure of the mass curve from the demand line represents the reservoir capacity required to satisfy the demand (Figure 27).

The disadvantages of this method are:

i) the analysis is based solely on a historical record which may not include an adequate range of wet and dry conditions;
ii) there is no means of assessing the risk of water shortage, particularly if the run of the record is short; and
iii) the optimum solutions are sensitive to the initial state of the storage system.

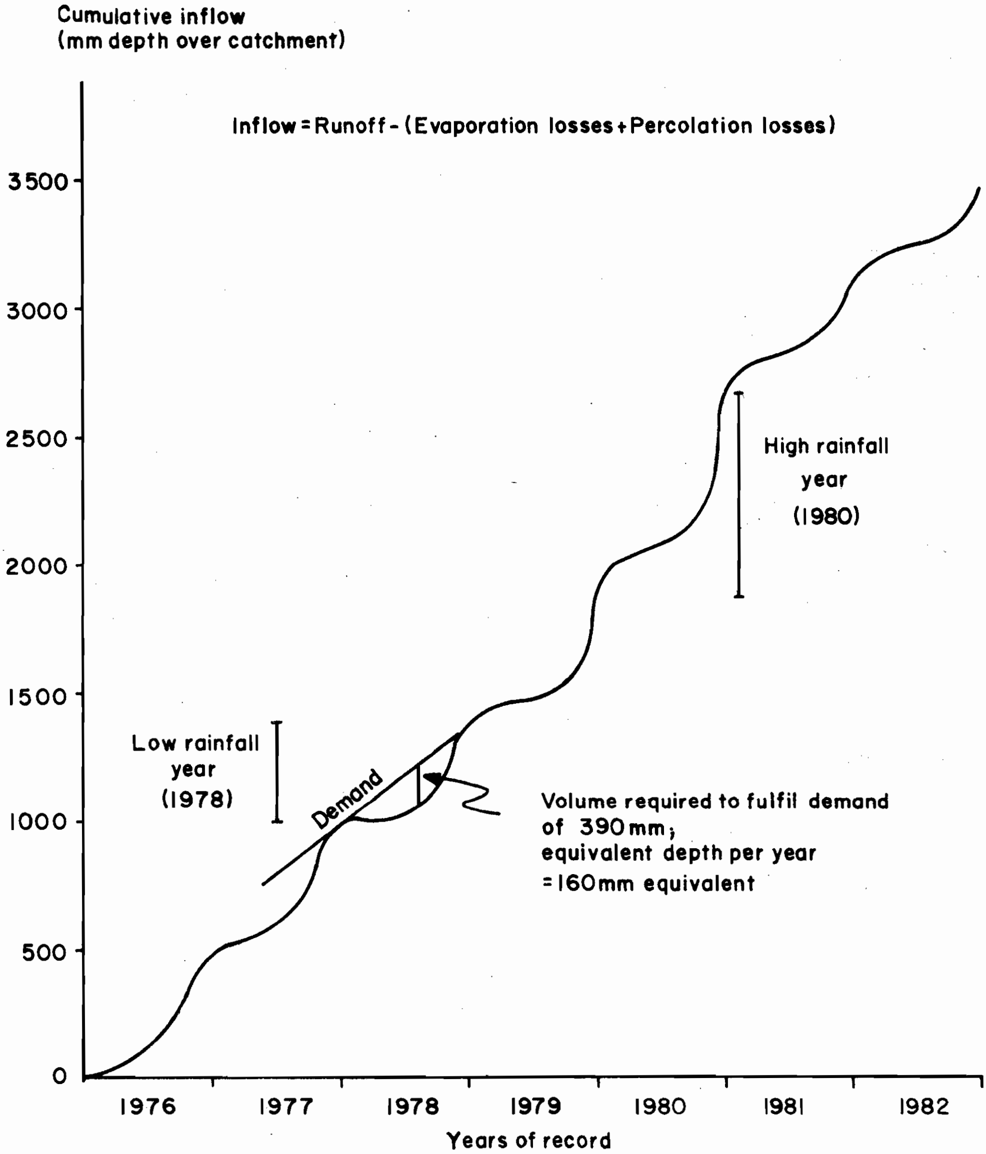
An alternative solution is to generate sequences of streamflow from an extended time series of rainfall. This will allow the probability of failure of the water supply to be assessed. Such factors as decreasing storage due to sedimentation and varying demand can easily be assimilated into this type of analysis (Carr and Underhill, 1974).

With the type of small reservoir designed for livestock watering in the semi-arid tropics, the limiting factors will almost certainly be high evaporation during the period of maximum demand and unreliable rainfall to replenish the reservoir. Under these conditions the use of techniques to suppress evaporation, such as those described in UNITAR (1982), may be considered worthwhile. These include the use of monomolecular films to introduce a diffusion barrier between water and atmosphere (see also Mansfield, 1959), the use of floating vapour barriers such as wax-impregnated, expanded polystyrene, and the use of compartmented reservoirs.

Compartmented reservoirs are designed to reduce evaporation by concentrating water into a number of deep compartments, rather than allowing it to spread over a large surface area. Pumps are required to transfer the water from one compartment to another as the storage decreases (Figure 28). It is reported that portable, high-capacity pumps make this method economical for small reservoirs (UNITAR, 1982), although this needs to be tested under African conditions.

Another method of evaporation control is to use sand rivers as storage reservoirs. This technique has been used successfully in East Africa (Ministry of Agriculture, 1962) where the reservoirs are known as subsurface dams. The technique depends for its effectiveness on the availability of an extensive bed of coarse sand of the kind normally found in Precambrian basement areas. By constructing a low weir at a convenient rock bar, coarse particles can be encouraged to settle upstream of the weir. If the height of the

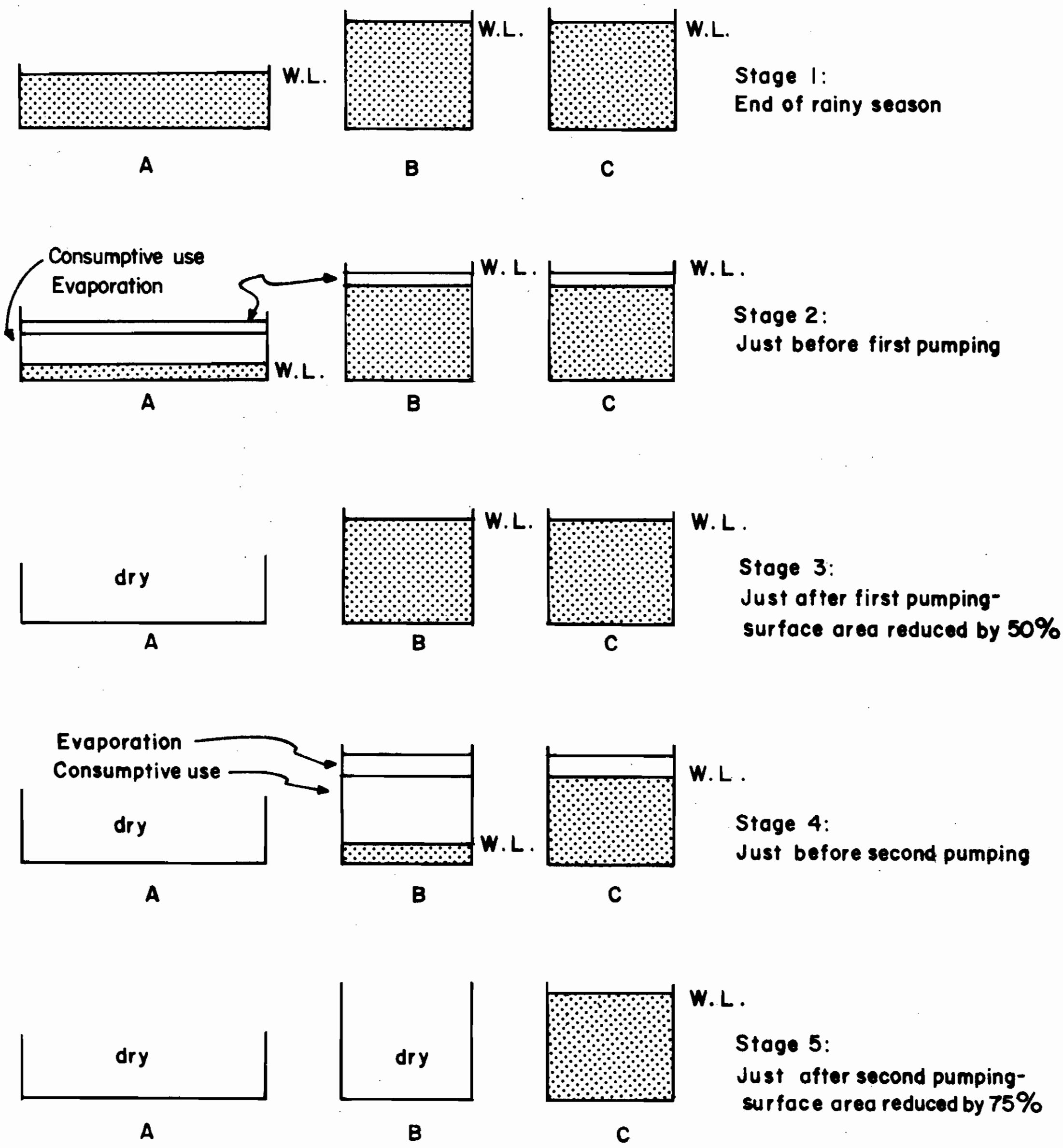
Figure 27. *A mass curve or Rippl diagram.*



weir is raised after successive floods, fine particles tend to be carried over the weir and a deep bed of coarse sand can build up. An abstraction pipe can be built into the lower stages of the weir with a suitably graded filter, rather like the screened casing and gravel pack of a borehole. With careful construction, such subsurface dams can function without trouble for many years. The storage capacity of the reservoir is limited by the void ratio of the coarse sand matrix, however, and its maximum value will range between 30 and 50% under favourable conditions. Well chosen sites can drain quite considerable stretches of river, albeit slowly, and this method can sustain small livestock populations throughout the dry season. No particular skill is required in constructing the low weir, and pipes can be laid to cattle troughs, incorporating valves or taps to control wastage.

The useful life of a normal surface water reservoir in tropical Africa is critically dependent upon the degree of soil erosion in the catchment. Heavy silt loads from eroding catchments can significantly reduce the storage available within the space of few years, and often in one wet season. Degrading catchments also change their storm runoff characteristics, so that flash floods become more frequent and more destructive. This can lead to overtopping and breaching of dam walls.

Figure 28. *Operation of a three-compartment reservoir.*



Schematic cross-sectional diagram of a three-compartment reservoir (A,B and C) showing water levels (W.L.) of various stages in the annual cycle of operation.

Source: UNITAR (1982).

Stromquist (1981) reports a number of reservoirs in Tanzania which have either lost a large proportion of their storage (e.g. 47.5% and 40.7%) or their embankments have been breached due to overcultivation, overgrazing and a high rate of firewood extraction.

If surface water reservoirs are contemplated, not only will the problems of reliability and sedimentation have to be faced, but also the pollution and health risks referred to in Chapter 5.

6.3 GROUNDWATER EXPLOITATION

The occurrence of groundwater has been discussed briefly in Chapters 3 and 4. If an area proves suitable for exploiting the groundwater resource, deduced either from surface and subsurface exploration or from the prior existence of shallow wells or boreholes, the most important criterion determining how the resource should be exploited is depth to static water level.

If the water level is less than 10 m from the surface, it will be relatively cheap and quick to dig a well by hand. Such wells are known to have been dug to great depths (e.g. Wagner and Lanoix, 1959, report depths of over 120 m). The relative costs of a lined or partially lined well dug to more than 20 m and a low-cost borehole of the type described below, however, mitigate against the hand-dug well, if drilling rigs are available. If they are not, hand-dug wells will continue to be constructed to considerable depths, even though they may not represent the most economical option.

One advantage of a dug well over a borehole is that community participation is assured from the start. Self-help labour is usually used to dig the well, and women and children can all help with the fetching and carrying of sand and gravel. A rural community thus identifies itself with the construction of the dug well, and this sense of communal ownership is vital if the water point is to continue to function.

Recently groundwater supply projects have started in Malawi, which integrate dug-well construction with low-cost borehole construction. The self-help concept, known to work successfully with well digging, is developed as far as possible with borehole drilling, and often a rural water supply will consist of a mixture of boreholes and dug wells, all constructed as part of the same programme. In this way community participation in siting, construction, completion and maintenance is encouraged, so that village-level operation and maintenance becomes a possibility.

The method of exploiting a groundwater resource will also depend on the facilities and funds available. The 'United Nations International Drinking Water Supply and Sanitation Decade' (IDWSSD) has focused attention on the plight of most of the rural population of tropical Africa. The very size of the task of providing the bulk of the rural population with safe but untreated water, within a short walking distance, makes it imperative that low-cost solutions be sought. With very few exceptions the cheapest per caput constructions will be dug wells and low-cost boreholes. The exceptions are when aquifers are deep lying, necessitating large drilling rigs and expensive boreholes.

The same principles apply equally well to water supplies for livestock. So many water points are required over such a large area that low-cost solutions are essential. The critical difference lies in the fact that with livestock enterprises some rate of return on investment is envisaged and, therefore, the more expensive options may be justified. In the case of village or community water supplies, no income is generated from the sale of water in the majority of rural areas in tropical Africa. Investment in water supplies for rural communities, therefore, has to be set against indirect benefits such as improvements in health and the release of women's time now spent in water collecting, so that the per caput cost needs to be kept as low as possible.

For this reason, this report concentrates on recent developments in low-cost technology applied to rural water supplies. This is a rapidly changing field stimulated by the IDWSSD, and the range of options will undoubtedly multiply as the decade progresses. The more expensive options centring around high-yielding boreholes, possibly motorised and with a reticulation system, will require professional advice on location, design, construction and development. These topics will be dealt with in outline.

6.3.1 Dug wells

Hand-dug wells are one of the oldest means of water supply. Begun as simple water holes in sand rivers, the concept of finding water by digging in riparian areas has spread away from the river course itself and, particularly in West Africa, deep hand-dug wells, reaching up to 100 m in depth, are used to tap deeper shallow aquifers and areas of basal seepage around inselbergs and escarpments.

Some loss of skills and knowledge of techniques for exploiting traditional sources seems to have occurred recently. UNESCO have a major regional project designed to identify and document traditional techniques for water resources development, which were known to have been successfully exploited within certain areas (UNESCO, 1982). The aim of the project is to transfer such appropriate technology within the sub-Saharan African countries, so that communities can adopt and extend the techniques with a minimum of outside assistance.

Improvements in well-digging techniques are mainly aimed at making the work easier and safer and, at the same time, improving the sanitary completion of the well to prevent pollution. Open wells afford very little protection against pollution, even when low parapets are constructed to prevent the ingress of surface water. Any water-lifting techniques involving the introduction into the well of ropes and buckets which are handled or have been exposed to contamination will create a possible source of faecal pollution. This risk has to be balanced against the extra cost of sanitary protection. The degree of protection, therefore, will depend largely on the individual circumstances of a particular water point. More sophisticated lifting devices, such as hand pumps, will require maintenance of one sort or another. If no maintenance facilities can be provided because of remoteness or lack of sedentary populations, open wells will be a better option. If, on the other hand, the hand pump is suitable for village or community level maintenance, and the frequency of use of the water point is high, it is preferable to aim for a fully protected well.

The simplest type of hand-dug well, therefore, is a wide (> 1 m in diameter) circular hole, dug as far as possible beneath the static water level. It is desirable to protect the sides of the well from collapse, and a common technique is to either sink pre-cast concrete rings or to mould rings *in situ*. These rings clearly determine the diameter of the well and they are usually designed to allow one or two men enough room to work inside them (i.e. at least 1.3 m in diameter).

Where the geological conditions allow free-standing well sides which are not likely to collapse, an alternative is to confine the lined portion of the well to the bottom of the hole, extending to about 1 m below the water table. This allows the hole to be backfilled on top of a concrete slab, which seals off the reservoir. This type of well must have a hand pump, and two serious disadvantages are immediately apparent: if the hand pump breaks down, there is no alternative means of abstracting water; and if the water level drops significantly in drought years, there is no easy way of deepening the hole.

Undoubtedly, the depth of lining will be a major cost factor in the construction of the well. More experimentation is needed with alternative materials, such as brick lining or sisal cement, to minimise the cost. This is particularly relevant in areas where dug wells exceed 20 m in depth.

Basically, the dug well provides a reservoir of groundwater which can be exploited by pumping or lifting with buckets. The capacity of this reservoir must be sufficient to meet the needs of the community. Normally, intermittent abstraction will allow some recovery (especially overnight) and, provided the storage is sufficient to meet peak demands, dug wells can perform successfully in areas of low permeability. The diameter and the depth of the well have little effect on its potential 'yield' with reference to the aquifer. They do determine the storage capacity, however, and the peak demand must be calculated in terms of the human and livestock populations to be served and the duration of abstraction.

The reservoir is usually constructed of porous concrete rings set below the static water level, with either non-porous rings, brickwork or backfilled material above. The depth below the water table to which rings can be set will depend on how effectively the well can be drained to allow digging. If small, dewatering motor pumps are available, this will considerably ease the enlargement of the reservoir. There is a practical limit to the depth from which a suction pump can lift water, and unless exhaust facilities are provided, motor pumps producing carbon monoxide should not be placed down the well. Electrical, submersible sludge pumps are very suitable for this task, but they require a generator and are generally not so readily available. Dewatering by hand is possible, but it is laborious and slow. It usually results in the reservoir not being constructed deep enough, and may result in failure of the water supply in drier-than-average years.

For this reason, well digging should take place at the end of the dry season when static water levels are at their lowest. The depth and diameter of the storage reservoir should be chosen to provide over half the daily requirement, and preferably nearer two thirds, assuming a 12-hour pumping day. A reservoir 3 m deep and 1 m in diameter, for example, will have a storage capacity of 2356 litres.

Some indication of the potential yield of a shallow well can be obtained by simple pumping tests. To carry out such tests, a means of measuring the water level, a pump or system of rapidly removing water by buckets and, preferably, a measuring trough with a 'v'–notch outflow are required. Water is abstracted at a rate such that the static water level is depressed to the minimum position. This position should correspond to where the intake of a hand pump would be placed, or to the minimum depth in the reservoir which allows water to be abstracted by bucket. The rate of abstraction is adjusted so that the water level remains constant at this position. It can then be measured from the flow over the 'v'–notch in the measuring trough. In areas of low permeability it may be impossible to obtain a continuous rate of pumping low enough to assess the aquifer yield. In this case buckets will have to be used to estimate the maximum abstraction rate in relation to aquifer yield. In areas of high permeability, on the other hand, it may be impossible to draw down the static water level with the pump available. In this case, however, there is rarely any concern that the yield will be insufficient.

In low-yielding wells an approximation of yield can be made by observing the rate of recovery to static water level. The well is bailed dry and measurements of the water level are taken every minute until static water level is restored. The rise of water level and the times must be carefully recorded. It will be seen that recovery is rapid at first, gradually slowing down to zero as the static level is reached, at which point the pressure in the aquifer is balanced by atmospheric pressure. The volume of the well per unit depth being known, the number of litres recovered and minutes elapsed can be tabulated or plotted as a graph, which will show a flattening curve (Figure 29). An approximate yield can then be determined by averaging out the values in the lower two thirds of the curve, or in the first two thirds of the table, neglecting the flatter portion where recovery asymptotically approaches static level.

Many different designs of protected dug wells can be found in the literature (e.g. Wagner and Lanoix, 1959; US Public Health Service, 1950; UNDP/Malawi Government, 1982; DHV, 1979), and two examples of contrasting design are given in Figures 30 and 31. The advantage of the completely lined well is that even if a hand pump is fitted, it can be provided with a removable manhole cover to allow buckets to be used in the event of a pump breakdown. It is also possible to deepen an open or fully lined well in times of drought.

In completing the well at the surface, whether it is left open or covered with a slab and a pump, it is important to seal or grout the top of the well to prevent contaminated surface water from infiltrating down to the water table. This is particularly important if porous linings such as clay bricks are used in the upper part of the well. A minimum of 3 m of grouting is recommended by Wagner and Lanoix (1959). In very porous subsoils not only will careful attention have to be paid to this aspect, but also the well will have to be sited away from sources of organic pollution (see Chapter 5). It is also desirable to raise the well wall above the level of the ground surface. Open wells should have a wall high enough to remove the risk of people overbalancing and falling into the well (> 50 cm). If a pump is provided, it is good practice to extend the outlet pipe to 3 m or more from the slab. This will help prevent waste water infiltrating back into the well.

The standard practice in Malawi (UNDP/Malawi Government, 1982), where a hand pump is fitted to either a dug well or a borehole, is to construct concrete aprons at the end of an extended outlet pipe and drainage channels to lead waste water even further away from the water point (Figure 30).

An alternative to the wide-diameter shallow well is the driven well point. Its application is limited to shallow sandy aquifers, normally not more than 10 m below the surface. Being of small diameter, usually a nominal 50 mm or 100 mm, they can only accommodate a small pump with a low rate of delivery. They can serve a limited number of livestock, however, and can be a very useful adjunct to an open watering hole, such as a *hafir* or swamp, to provide relatively clean and safe drinking water to the stock owners.

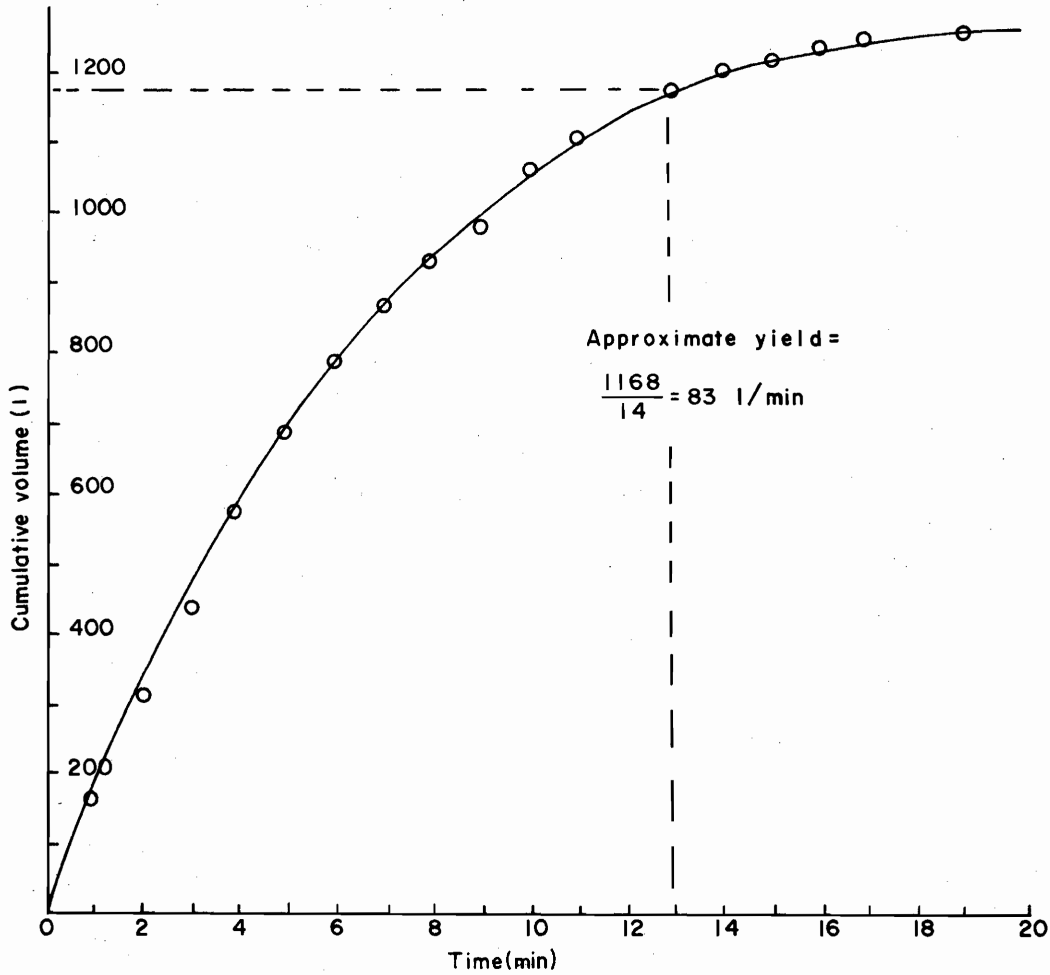
The well consists of a length of perforated steel pipe, around which wire gauze has been wrapped or, preferably, bronze screening of fine mesh. The leading end terminates in a steel cone which should be of slightly larger diameter than the pipe. The upper end is connected to successive lengths of screwed steel piping to form a column which is driven into the ground by vertical blows of a hammer. The hammer may be worked by hand or suspended from a pulley. With small diameters of less than 75 mm, the water is abstracted by a suction pump coupled directly to the protruding pipe. Larger diameters of 75 to 100 mm will accommodate a 50 mm cylinder with a plunger connected by well rods to a conventional hand pump. The cylinder can draw water from depths greater than the suction limit of 7 m.

6.3.2 Boreholes

Boreholes are also termed 'wells' in American literature and are referred to as 'tube wells' in the Indian subcontinent. They are small-diameter (100 to 120 mm) drilled holes, constructed by mechanical means to depths ranging from 20 to 1000 m. The diameter of the hole is related to the type of pump to be used and to the potential yield of the aquifer. Large-diameter boreholes are usually motorised and constructed in high-yielding aquifers. Their high cost usually only justifies their use for urban or peri-urban water supplies and for irrigation schemes.

Assuming that the most important criterion in providing water supplies for livestock is minim-

Figure 29. *Typical recovery test of a shallow well with a volume of 8 l/cm depth.*



ising cost, it follows that borehole diameters and depth must be kept to a minimum. For a given livestock population and given aquifer conditions, the optimum solution may be either a series of small, low-yielding boreholes or a single high-yielding borehole. The exact combination or configuration will depend on individual circumstances.

Hand-pump cylinders generally require an internal diameter of 100 mm. If the borehole is drilled in unconsolidated or partially consolidated formations, a gravel pack will be needed to prevent the ingress of fine particles which tend to cause excessive wear on pump parts or silting-up of the borehole. The gravel envelope should be a minimum thickness of 50 mm, and this requires that the drilled hole be at least 200 mm in diameter. If the borehole is drilled in hard rock, no gravel pack is necessary. In this case the hole diameter can be reduced to 100 mm.

With regard to depth, the general principle to follow is that the borehole should be no deeper than necessary. It follows that after water is struck, a decision has to be made when to stop drilling. If a hydrogeologist is supervising the borehole programme, a decision will be taken based on the aquifer thickness and permeability. Bailer tests at 3 m intervals can give an indication of the potential yield as drilling progresses. The hydrogeologist has to make a judgement based on the indicated yield and on the possibility of seasonal or annual fluctuations in water level effecting the adequacy of saturated aquifer thickness.

In the weathered basement rocks, 10 to 15 m of saturated aquifer have usually been sufficient to give yields of 0.5 l/sec or more (UNDP/Malawi Government, 1982). Dijon (1971), in dealing generally with the Precambrian crystalline basement in Africa, also recommends the less clayey, weathered horizons as being the best yielding

Figure 29. Continued.

Depth below datum	Rise (cm)	Rise (l)	Cumulative volume (l)	Time (min)
5m 20 cm	0	0	0	0
00	20	160	160	1
4m 82 cm	18	144	304	2
65	17	136	440	3
49	16	128	568	4
35	14	112	680	5
22	13	104	784	6
12	10	80	864	7
04	8	64	928	8
3m 96 cm	6	48	976	9
90	6	48	1024	10
85	5	40	1064	11
80	5	40	1104	12
76	4	32	1136	13
72	4	32	1168	14
69	3	24	1192	15
67	2	16	1208	16
65	2	16	1224	17
63	2	16	1240	18
62	1	8	1248	19
61	1	8	1256	20
61	0	0	1256	21

aquifers and counsels against drilling into fractured rock. He suggests 1 to 1.5 l/sec as being a good yield to aim at in this type of formation. Bannerman (1973) reports more variable yields (0.1 to 1.6 l/sec) from the weathered profile of igneous and metamorphic rocks in Ghana, where the presence of 'kaolinic porridge' or 'flowing arena' complicates construction.

The Kenya Master Water Plan (TAMS, 1979) quotes median yields from the three major categories of rock formations as being 0.7 l/sec for crystalline basement rocks, 1.1 l/sec for sediments and 1.6 l/sec for volcanics. Median specific capacities are highest in the sediments (10 l/min/m) and significantly lower in the volcanics (3.3 l/min/m) and basement rocks (1.6 l/min/m). This gives an indication of the average aquifer thicknesses which are needed to give a yield of 0.5 l/sec: sediments 3 m, volcanics 9 m and basement rocks 20 m.

The above figures must be used with caution because yield and specific capacity are functions of both aquifer characteristics and borehole design. Many of the older boreholes (on which the statistics are based) were poorly designed, and often poorly constructed, in that they 'cased-out' the high-yielding horizons. This is particularly true of boreholes drilled into crystalline rocks of the Precambrian basement. Unless the borehole strikes a fissure, the active aquifer is passed through and unslotted casing is used for most of the water-yielding strata. Recharge is solely dependent on infiltration from the weathered zone down the outside of the borehole casing, resulting in very poor yields.

Borehole design. A good borehole for rural water supplies based on hand pumps should give a sand-free sustainable yield of not less than 0.25 l/sec and preferably 0.5 l/sec. The conventional method of ensuring sand-free water in unconsolidated sediments is to place a gravel pack around the slotted screen which allows water to pass from the aquifer to the pump. The purpose of the gravel pack is to prevent small particles from migrating with the flow of water through the slotted screen.

Figure 30. *Example of a back-filled dug well.*

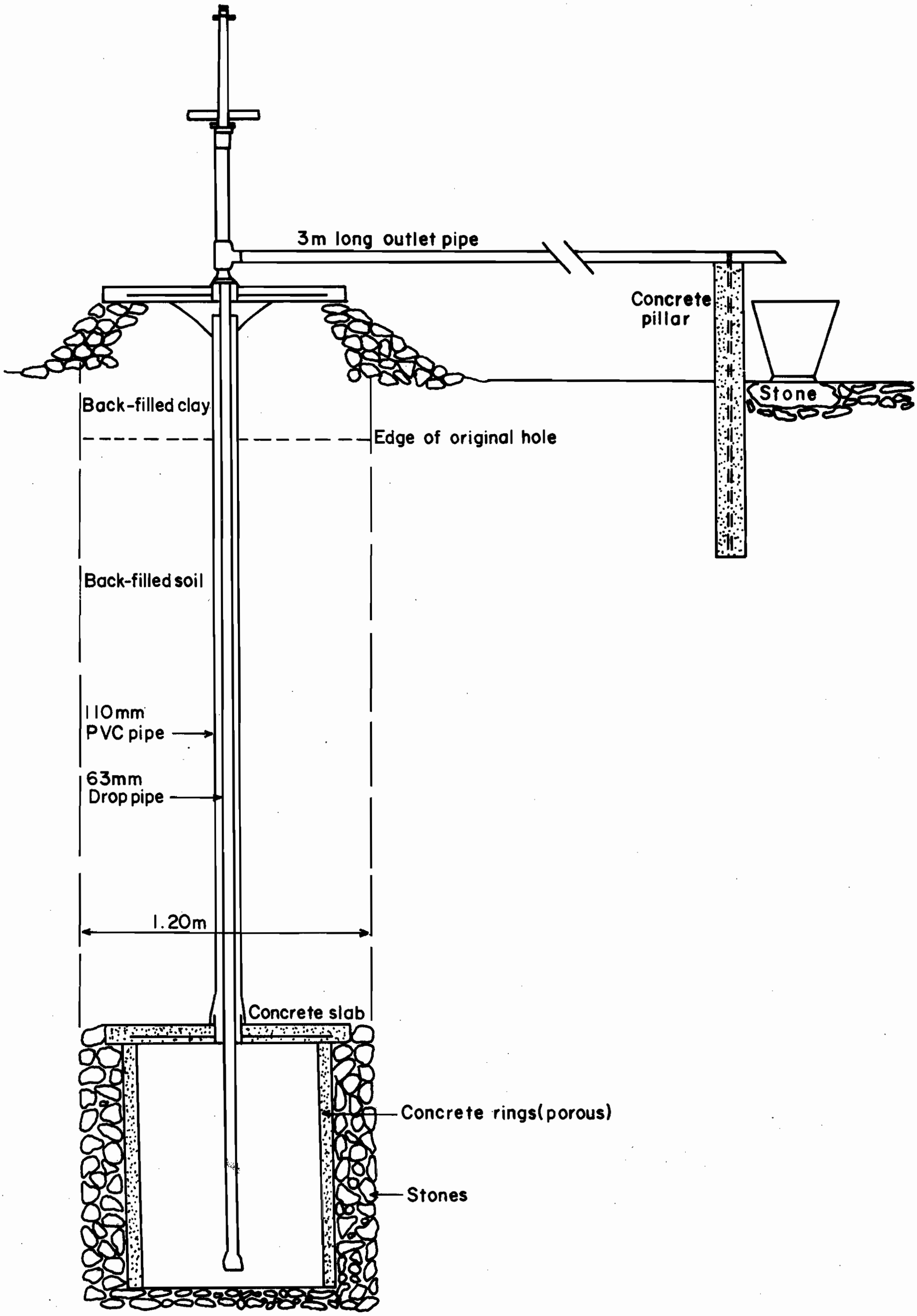
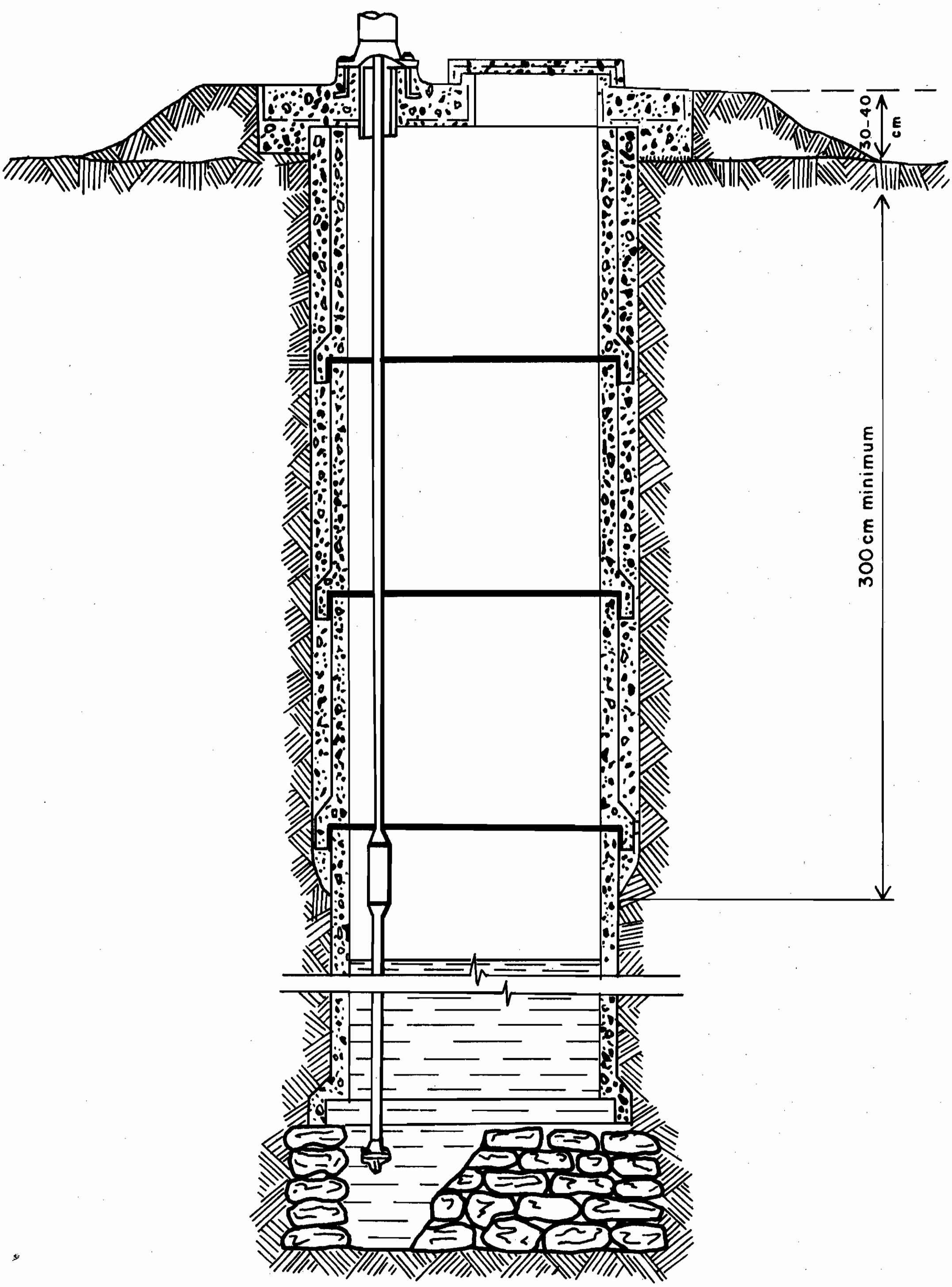


Figure 31. *Example of a fully lined dug well.*



Source: Wagner and Lanoix (1969).

It should, ideally, be carefully chosen so that the particle size distribution in the gravel pack gives good permeability, but the pores are too small to allow the passage of the majority of the grains in the aquifer. The ratio of median grain size of pack and aquifer is termed the 'pack-aquifer ratio' (P-A) and the optimum P-A ratio will depend largely on the degree of sorting of both materials. Conservative P-A values of 5 to 8 are recommended by UNDP/Malawi Government (1982). Thus, for the median grain size of 0.2 to 0.3 mm found in the weathered crystalline formations in Malawi, a gravel pack with a median grain size of 1.0 to 2.4 mm has been chosen. Coarse quartz sand, which occurs as well graded beach sand at certain sites around Lake Malawi, has been found to be an almost ideal gravel pack.

The common practice of using crushed roadstone chippings of 6 to 12 mm in size is to be avoided since these will not act as a properly graded gravel pack in excluding sand particles from the borehole. This will lead to excessive wear of pump parts and high maintenance costs. The generally accepted range of gravel pack thickness is 75 to 150 mm. If well graded sands are available, of the correct median grain size, the diameter may be reduced to 50 mm to minimise costs.

Once the median grain size of the gravel pack is established, the screen slot size can be chosen. Expensive stainless steel screens with a variety of slot sizes are available on the market. Cheaper materials have been used successfully (GRP, ABS and PVC) even where permeabilities are low. Slotted PVC casing (110 mm Class 10 pipe) is used extensively for all low-cost boreholes in Malawi. The slot size and open area, i.e. percentage of open slot area to the total area of the screen, are the important criteria. Slot size should be chosen to minimise the passage of the graded sand gravel pack through the slots, and a size equal to the d_{10} of the sieve analysis (i.e. where 90% of the graded sand cannot pass through the slot) will be adequate. With the slotted PVC casing used in Malawi the d_{10} of the gravel pack is 1 mm and the slot size is 0.75 mm, giving a further margin for safety.

Open area should be matched as closely as possible to the effective porosity of the gravel pack and the aquifer. To reduce the flow velocity through the slots, which will assist in stabilising small particle movement, sufficient length of slotted casing should be used to give the required yield in relation to the aquifer permeability and desired maximum entrance velocities. Open areas of 8% have been achieved with locally manufactured, slotted PVC casing in Malawi. Typical analyses using yields of 0.5 l/sec and maximum entrance velocities of 1.5 cm/sec show that 1.5 m of slotted casing are adequate in the weathered crystalline formation in Malawi (UNDP/Malawi Government, 1982).

The above guidelines indicate that the torch-cut or hacksaw-cut steel slotted casing, commonly used in developing countries, has a completely inadequate open area (frequently less than 1%), and torch-cut slots in particular are much too wide (3 mm). Boreholes constructed with this type of slotted casing and often with the wrongly graded gravel pack have low yields and are very susceptible to sand incursion. The high construction costs of boreholes are only justified if their design is matched to the aquifer characteristics. Poorly designed boreholes may well silt up within a very short time and, at the very least, will require constant and expensive maintenance.

Construction. The method of construction of a borehole will depend upon the depth and diameter required, the nature of the geological formation to be penetrated, and the amount of back-up support available. Table 17 gives an indication of performance of the four major methods in relation to the cost of operation and degree of skilled labour required. If minimising costs is the most important factor in providing water supplies, the smaller rigs, although very much slower in operation, are to be preferred to the large and sophisticated multipurpose rotary rigs. If, on the other hand, a large number of boreholes are to be drilled to considerable depths in semiconsolidated or consolidated formations, speed of drilling may become an important factor and the most cost-effective solution may well be to use the more expensive rig. One important point, however, must be borne in mind. Rotary rigs require not only skilled operators, who are in very short supply in developing countries, but also sophisticated repair and maintenance facilities. The simpler rigs can often be repaired without recourse to such facilities, and their longevity and actual rate of production (number of boreholes per year) compare very favourably with rotary rigs.

Hand drilling is the cheapest and simplest form of percussion drilling. This method can be successfully used for boreholes up to 15 m in unconsolidated formations. In Kenya hand drilling with simple percussion rigs originally designed for exploratory work achieved rates of drilling of 5 m per day in unconsolidated material (Ministry of

Table 17. *Comparison of different drilling methods.*

	Hand-operated rig	Cable-tool rig	Small air flush rotary rig	Large multi-purpose rotary rig	
Capital cost	very low	low to medium	medium	very high	
Running cost	very low	low	medium	very high	
Training needs for operation	low	low to medium	medium	very high	
Repair skills	very low	low to medium	medium	very high	
Back-up support	low	low to medium	medium	very high	
200 mm holes to 15 m in unconsolidated formation	fast	fast	impossible	very fast	Constraint is mobilisation time
200 mm holes to 50 m in unconsolidated formation	very slow and difficult	fairly fast	impossible	very fast	
200 mm holes to 15/50 m in semi-consolidated formation	impossible	fairly fast	impossible	very fast	
100 mm holes to 15/50 m in consolidated (hard) formation	impossible	very slow	very fast	very fast	

Source: UNDP/Malawi Government (1982).

Agriculture, 1962). In the Morogoro area of Tanzania a simple, hand-operated, rotary system has been developed successfully and used to construct boreholes up to 20 m in depth (DHV, 1979).

For most general purposes the hand-drilling methods are too slow and too limited. Cable-tool drilling rigs use motor power to raise the chisel tools which drill with a percussion action. Many different sizes and designs are available. The smaller rigs are very manoeuverable and much easier to position at sites which have difficult access. They are not always satisfactory, however, when obstructions are met in the drilling operation for which heavier tools are required. The larger percussion rigs are more than adequate for low-cost boreholes drilled into the weathered crystalline formations, and have heavier tools which can be used in more consolidated formations. Most percussion rigs of this type are truck- or trailer-mounted and they are able to penetrate difficult terrain where the much heavier and larger rotary rigs are unable to go.

The drilling operation consists of raising and lowering a string of tools suspended from the drilling cable (Figure 32). Water is added to the hole above the water table and the cuttings from the bit are removed periodically by a bailer. In soft ground the hole is cased with flush-jointed drilling casing to prevent the hole from collapsing. The casing is allowed to fall under its own weight, or it can be driven down as drilling progresses. When the hole has reached the desired depth, slotted and plain borehole casings can be inserted and centred within the drilling casing. The gravel pack is then poured and the drill casing can be pulled out.

The 'hydraulic rotary method' uses a rotating bit with hardened cutting edges attached to hollow tubes through which drilling mud is forced to the working face in the hole (Figure 33). Drilling muds and fluids are special clays, such as bentonite, which give a range of viscosity and specific gravity. Pumped under pressure from the surface, they convey the cuttings through the annular space between the tubes and the sides of the hole to the surface, where they are settled out in a series of ponds. The mud is then recirculated down the hole. The drilling operation has to be continuous to keep the mud constantly in motion. Drilling bits are of many types and hardnesses, designed to deal with all kinds of ground formation and rock.

Casing is not normally required during the rotary drilling process because the circulating mud keeps the hole open. Casing is inserted when the drilling is completed, according to the needs of the formation. This is normally done for the first part of the hole (when it is in soft ground) down to the firm rock, below which casing should not be necessary.

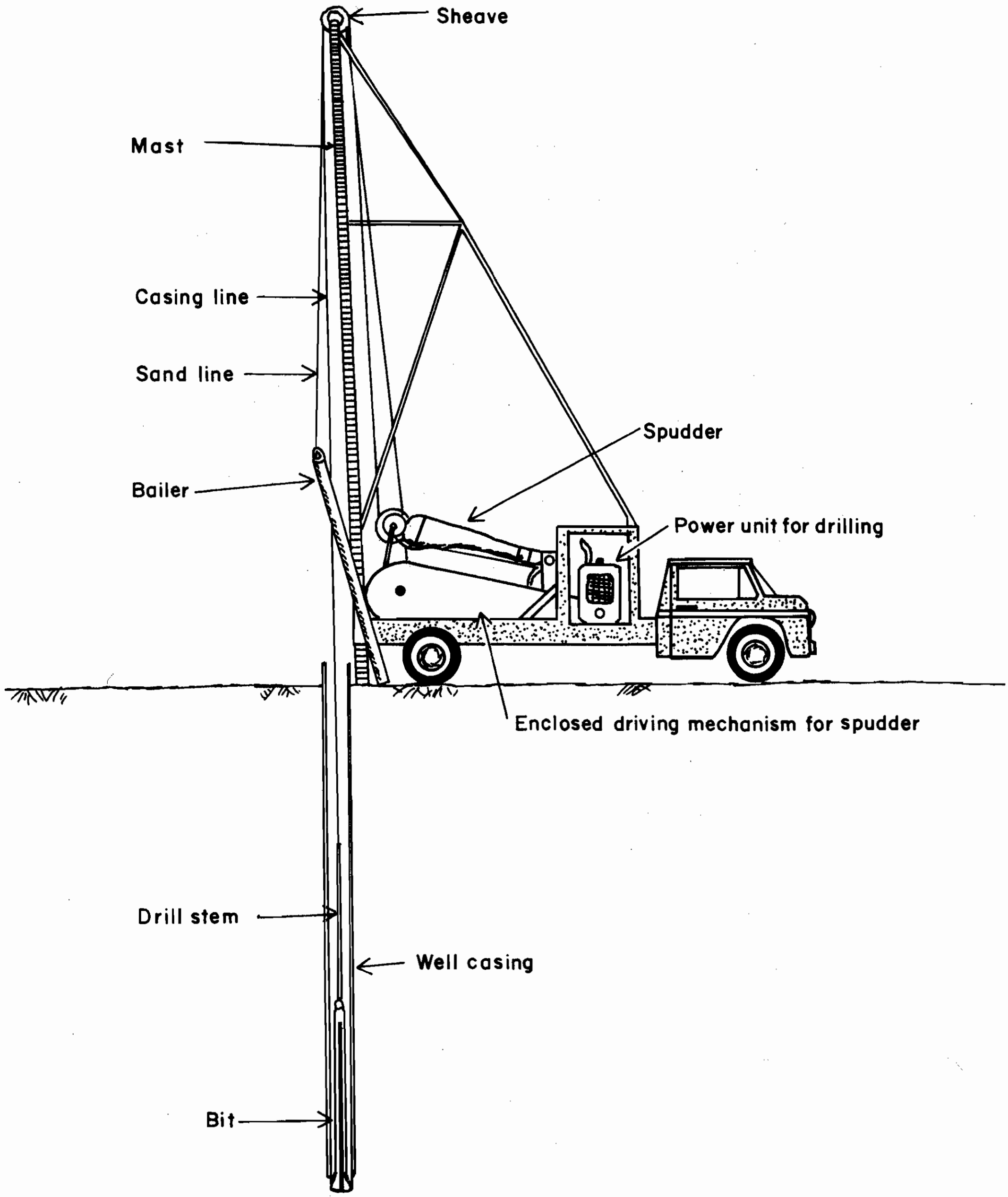
Rotary hydraulic rigs are very fast in soft ground with an output of 100 m or more per 24 hours. They are also very fast in hard rock if the correct bit is used. Hard rock bits wear quickly, however, and are costly to replace.

The equipment of a rotary rig, which is commonly mounted on a self-propelled six-wheeled vehicle, comprises a prime mover, normally a diesel engine of 100 to 200 hp, a hydraulic pump for actuating the various controls and the rotary movement of the drill stem, and a high-capacity centrifugal pump for mud circulation. Ancillary equipment such as an electric lighting plant, welding sets, grinders, water trailers or tankers and fuel bowsers make up a formidable complement which, in total, may weigh some 50 t. Capital investment of this magnitude can be justified if one remembers that such a rig can finish a 200 m hole in less than a week. Profitability, however, will depend on continuous employment of the equipment.

The 'reverse circulation method' uses the same type of rig as the hydraulic rotary method, but the principle is different. Here the cuttings are removed by water drawn up through the drilling tubes by a suction pump at the surface. This requires a constant head of water to be kept above the rest water level of an aquifer. The hydrostatic pressure keeps the sides of the hole open, and this is assisted by fine particles of clay and sand from the cuttings, which are returned with the circulating water and which line the sides. It is essential to keep the hole full of water, as failure of the hydrostatic pressure could cause the collapse of the sides and the loss of expensive tools. This method is most suitable for drilling large-diameter holes (up to 1200 mm) in unconsolidated formations.

The 'down-the-hole hammer' combines the features of percussion drilling with those of rotary drilling, using compressed air to drive a rotating pneumatic hammer at the end of the string of tools. Exhaust air from the hammer, issuing from ports, travels at high velocity (1000 m/min) and removes the cuttings. This type of rig is smaller than a rotary rig and more compact. It is normally mounted on a self-propelled chassis and energy is supplied by a powerful compressor driven by a diesel engine of up to 200 hp. Compressed air is used to drive various motors for raising and lowering the drilling string as well as operating the ham-

Figure 32. *Diagram of the cable-tool (percussion) method of drilling.*

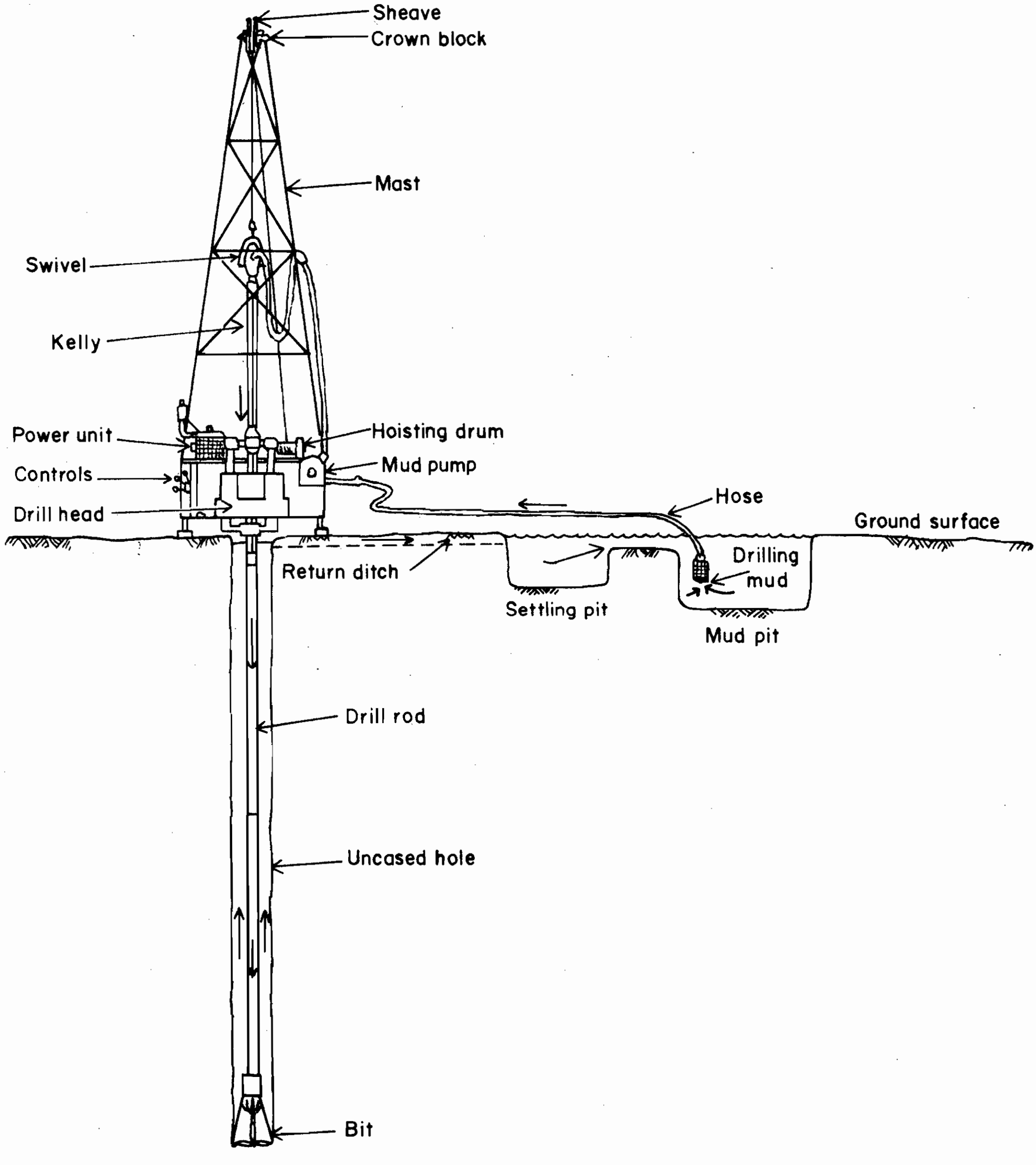


Source: Davis and De Wiest (1966).

mer, and must be supplied at a pressure of between 100 and 200 p.s.i. (or 7 to 14 kg.cm^{-2}).

The down-the-hole hammer method of drilling for water has been developed from the technique of drilling blast holes in quarries using light compressed air rigs. The original concept was to drill small-diameter holes rapidly in hard rock. This was successful when quarrying in crystalline formations, but proved a failure in drilling through soft formations, largely because the supply of air was insufficient to compensate for losses in the loose ground. On reaching the water table in a sandy aquifer a stoppage of even a few minutes, which interrupts air flow, can result in clogging of the hammer which then will have to be stripped with special tools. In remote areas, if the tools and the skill to effect the repair are lacking, this can mean the loss of many working days.

Figure 33. *Major components of the rotary method of drilling.*



Source: Davis and De Wiest (1966).

Conventional down-the-hole hammer rigs, specifically designed for quarry work, are normally unsuited to water boring, but development of the principle over the past two decades has produced equipment which is well able to deal with aquifer conditions in hard ground. The down-the-hole hammer is faster in hard rock than the percussion or rotary bit. Improvements in hammer design and, above all, the provision of an adequate compressed air capability, have established the method in the field of groundwater development. Deep-seated aquifers underlying thick flows of fresh lava can be reached quickly and economically. For this reason manufacturers of rotary equipment include a large compressor and the hammer, tools and fittings in the complement of their units. A combination of rotary and down-the-hole techniques is often the answer to difficult subsurface conditions.

Development. After a borehole is constructed, it is 'developed' to stabilise the gravel pack and the formation immediately adjacent to the borehole. Development involves the creation of much higher water entry velocities into the borehole than would normally be encountered during pumping at the design discharge, together with 'backwashing' into the formation. It causes fine particles to move into the hole and encourages the rearrangement of the remaining particles into a more stable matrix. During normal pumping following development, therefore, the water is much cleaner.

Various development techniques can be used, such as surging with compressed air and surge blocks, and 'rawhiding' or overpumping. The choice of technique will depend to some extent on the type of slotted casing employed. PVC casing, for example, is vulnerable to damage when bailing is used to remove the fine silt settling at the bottom of a borehole. For this reason overpumping is usually preferred to surging in PVC-cased boreholes.

With well designed and properly constructed boreholes, overpumping is rarely required for more than 5 to 10 hours to obtain a sand-free discharge. If a high proportion of fine particles is encountered in the formations adjacent to the screen, this time will have to be extended until clear water is being pumped.

Borehole test pumping. After development, test pumping is usually carried out to provide information on the hydraulic characteristics or efficiency of the borehole and on the hydrogeological characteristics of the aquifer.

Data obtained from test pumping can be used to determine the specific capacity or the discharge/drawdown ratio. This gives a measure of the efficiency or productive capacity of the borehole and indicates at what level the pump should be set.

Test pumping for relatively low-yielding boreholes designed for hand pumps need only be carried out to ensure that the borehole is able to sustain an adequate yield. Aquifer tests and more elaborate test pumping are expensive and time-consuming, and are normally only carried out in a major development of an aquifer.

The simple tests should preferably be carried out at a rate higher than the maximum delivery of a hand pump, and continue for at least 4 hours. This will ensure that there is no danger of overpumping or pumping air during normal operation.

Under no circumstances should boreholes designed for hand pumps be motorised at a subsequent date without professional advice. Increasing the discharge of boreholes beyond their design capacity can cause irretrievable damage and often complete collapse.

6.4 WATER LIFTING DEVICES

Unless water is supplied under hydrostatic pressure from a surface source above the water point or from an artesian basin, a means of raising or lifting the water is required. From the earliest times man has found it necessary to raise water from a source to supply the needs of himself, his animals and his crops, and throughout the world much ingenuity has ben shown in devising appliances to make the task easier and quicker.

Beginning with the wood or leather bucket to bail water from a water hole, a stream or a furrow, the shaduf and the Archimedes' screw were developed and are still in use, as are many devices using animal power. In nomadic societies, water is still being raised from wells by leather buckets and ropes, or by a team of several men standing one above the other and passing the water upwards in small containers. To anyone who has observed this operation used to water a large herd of cattle the hourly output is impressive, and is witness to the energy which men are prepared to expend to safeguard their herds. Such traditionally developed methods, however primitive, are adapted to the situation and are an appropriate technology, if not always the most efficient. In contrast the reluctance of these same people, who are willing to expend great manual effort, to contribute money for the operation and maintenance of modern mechanical equipment is manifest in many instances, even if the money is there and the service is generally appreciated.

The appropriateness of any mechanical device is determined not only by its reliability and simplicity in operation, but also by its acceptance by the users. For example, it has been the East African experience in pastoral areas that attempts to replace the bucket and rope, or chain of men, with a hand pump, which allows the top of the well to be sealed and the water kept free from pollution, have not been successful because it was claimed by the users that the hand pump was more energy consuming and had a lower output. Hand pumps fitted on wells were neglected, frequently vandalised or abused to the point of breaking the surface equipment. They were soon discredited and abandoned.

In such circumstances some protection of the well was achieved by building a coping extending from some 2 m below the surface to some 60 cm above ground level. Capping it with a concrete lid allows a manhole to be installed, sufficiently large to allow the traditional bucket to be lowered should the hand pump fail. Cattle troughs arranged around the circumference were also a welcome improvement.

The hand pump has found acceptance in those areas of the tropics where the supply is mainly intended for human consumption, and where only small numbers of stock have to be watered. Much research has been done on devising a pump which would be cheap, robust and easy to maintain. Work still continues in several African countries and on a global scale with the UNDP/World Bank Rural Water Supply Hand Pumps Project. A number of good patterns of hand pumps have been developed and recent developments, particularly in Malawi, show that simple, robust hand pumps can be locally produced in developing countries, with a minimum of imported parts (UNDP/Malawi Government, 1982).

In countries where people live in quasi-nucleated communities it is possible to provide a communal water supply either by direct grant or by subsidy, and hand pumps fitted on wells or low-cost boreholes within easy walking distance (less than 1 km) are often the least-cost solution. The problem of maintenance still remains. Moving parts must be regularly greased and cleaned and wearing parts must be replaced from time to time, under normal working conditions. With the new types of village-level operation and maintenance hand pumps, maintenance becomes the responsibility of the community, but unless there is an organisation to set aside funds, however small, to employ a trained man or woman and to provide the parts and materials, breakdowns in the supply inevitably occur.

In recent times the development of water supplies for livestock and other uses has tended to rely heavily on the conventional pump imported from the developed countries at substantial cost. A wide variety of pumps suited to any given situation is available (Table 18). Where the supply is motorised, maintenance problems increase and, even in areas that are not so remote, reliability is a function of efficiency in supplying stocks of fuel and spare parts. If the supply should break down because of lack of transport over poor roads or because of failure to provide the necessary funds at the right time, much hardship will result, and stock may have to be moved to other, better watered areas, thus upsetting the grazing rotation pattern and further endangering the pasture.

With the rise in the cost of fuel, increasing attention is being paid to the development of alternative energy sources to drive pumps. The aim is to produce techniques which can remain unchanged in concept and design for the foreseeable future. Some of these methods are described below. In the nomadic areas of the arid and semi-arid zones, however, reliance on human energy will continue for a long time to come.

Where the keeping of livestock is a part of mixed farming activities, there may not be the human time or energy to spare for pumping by hand unless the water source is on the farm and the animals are few. The demand for easily available water continues to increase, and emphasis is now placed on developing community supplies, which include livestock water, in order to spread the capital cost over many consumers. This presupposes an adequate source which may lie some distance away from the point of use, sometimes as far away as several kilometres.

The simplest communal supply will take the form of an intake at the source, a pumping unit if gravity command is not available, a pipeline, a storage tank to hold a 2 days' supply, a distribution system to standpipes in the village, and a cattle trough away from the residential area.

The choice of the right pump for any particular situation is of the utmost importance. Experience shows that pumping problems are most often responsible for the breakdown or poor operation of small water supply systems. The most common types of pump for small water supply systems are:

i) hand- or power-operated reciprocating pumps with the pump cylinder above the ground;
ii) power-operated centrifugal pumps with the pump mechanism above the ground;
iii) hand-, power- or wind-operated reciprocating deep-well pumps with the pump cylinder in the well;
iv) deep-well turbine pumps, powered either from the surface or from a submersible electric motor;
v) jet pumps, power-driven at the surface; and
vi) hydraulic rams (Wagner and Lanoix, 1959).

Under ideal conditions the pressure of the air at sea level is enough to raise a column of water 10.3 m in a vertical pipe in which a perfect vacuum has been made. In practice the suction lift, i.e. the vertical distance from the pump cylinder to the water surface, is never more than 5 to 6 m. If the suction lift is required to be greater than 5 to 6 m, the pump cylinder should be lowered into the well.

Table 18. *Relative merits of pumps for use in small water supply systems.*

Types of pumps	Positive displacement			Velocity			
	hand pumps, plunger type	motor, wind-driven plunger type	chain or continuous bucket	centrifugal	deep-well turbine	jet	air lift
Efficiency range (%)	Low; can be improved with double-acting cylinders: 25 – 60%	Low; can be improved with double-acting cylinders: 25 – 60%	Low	Good: 50 – 85%	Good: 65 – 80%	Low: 40 – 60%	Low: 25 – 60%
Operation	Very simple	Simple	Very simple	Simple	More difficult; needs attention	Simple; air locks can cause trouble	More difficult; compressor needs attention
Maintenance	Simple, but valves and plunger require attention; more difficult when pump cylinder is in the well	Same as hand pump; maintenance of motors sometimes difficult in rural areas	Simple	Simple, but attention is necessary	More difficult and constant; skilled attention is necessary	Simple, but attention is necessary	Compressor needs constant attention
Capacity (l/min)	10 – 50	40 – 100	15 – 70	Very wide range: 5 to unlimited	Very wide range: 100 – 20 000	25 – 500	25 – 10 000
Head (m)	Low	High	Low	5 – 500	20 – 500	Low	Low
Cost	Low, but higher when cylinder is in the well	Low, but higher when cylinder is in the well	Reasonable	Reasonable	Higher, especially in deep wells	Reasonable	Reasonable
Advantages	Low speed; easily understood by unskilled people; low cost	Low cost; simple; low speed	Simple; easy to operate and maintain	Efficient; wide range of capacity and head	Good for small-diameter boreholes; ease of operation	Moving parts on surface; ease of operation	Moving parts on surface; can pump turbid and sandy water

Table 18. Continued.

Type of pumps	Positive displacement			Velocity			
	hand pumps, plunger type	motor, wind driven plunger type	chain or continuous bucket	centrifugal	deep-well turbine	jet	air-lift
Disadvantages	Low efficiency; limited use; maintenance more difficult when cylinder is in the well	Low efficiency; limited use; maintenance more difficult when cylinder is in the well	Low efficiency; limited use	Moving parts and packing require attention	Moving parts in well; rather expensive; requires good maintenance and operation	Limited application; low efficiency; moving parts require attention	Limited application; low efficiency; compressor requires constant attention
Power	Hand or animal	Wind, motor	Hand, animal, wind, motor	Motor	Motor	Motor	Motor

Source: Wagner and Lanoix (1959).

6.4.1 Selection of pumps

It is not possible to establish strict rules for selecting pumps. The most important considerations are:

i) capacity and lift required;
ii) initial cost of the pump and its driving equipment;
iii) cost of operation;
iv) the extent and reliability of the service which will be available for maintenance; and
v) the desirability of standardisation and reduction of the number and diversity of spare parts.

The following remarks can also be made:

1. Pumps in which all moving parts are above ground and easily accessible are preferable and will, in most instances, give the best service simply because they are easier to maintain with the means available in rural areas.
2. Where motor power is used efficiency is a very important factor, and the more expensive the power, the more important becomes the efficiency.
3. Centrifugal and deep-well turbine pumps must operate under the conditions for which they were designed, or a great loss in efficiency will result. Pumps with flat efficiency curves are to be preferred for rural water systems since they allow for greater flexibility in design.
4. Parts for the selected pump should be easily available and, preferably, manufactured within the country of use.

In selecting an engine, or prime mover as it is commonly known, a number of factors must be taken into consideration, the first being the duty required of it. The starting point is a calculation of the power required to lift a given quantity of water to a given height in unit time. The test pumping of a borehole gives the quantity that may safely be extracted from a given depth, taking into account the permissible drawdown and the depth at which the pump has to be set.

The total lift includes the vertical distance between the bottom of the pump cylinder or intake and the point of delivery at or above the surface, plus the friction loss in the piping which is expressed as a percentage of length (metres per 100 m). The friction factor varies with the diameter of the pipe, the material of which it is made, and the volume of water to be transmitted in unit time. Pipe manufacturers publish tables and graphs of friction loss, calculated for all measurements of pipe size, volume of water and distance.

The power to be supplied by an engine must be greater than the power required to lift the water because of efficiency losses in the transmission and in the pump itself. Other efficiency losses result from increases in altitude and in ambient temperature, compared with those for which an engine is rated.

The efficiency of the transmission system, of the well head of the pump, will vary according to the type and make, and will have to be estimated for each case if power is a critical factor and accuracy is required.

A rule-of-thumb for field use, which has generally been proved reliable, is to multiply power required to lift the water by a factor of 2.5 at the surface, or 3.3 at a depth of 100 m. To arrive at the actual brake horsepower of the engine, the required power thus calculated must be further adjusted by the derating factors for altitude and ambient temperature. Derating factors are given by the manufacturer for each type of engine. For example air-cooled, diesel engines, such as would be used on a borehole installation, are derated by 3.5% for every 300 m above sea level and by 2% for every 5.5°C above 30°C.

Having assembled the basic technical data for a borehole installation, including the required power of the prime mover, the designer is faced with the task of selecting the most appropriate type and make. All mechanical equipment must be robust, easy to operate and to maintain, economical in fuel and lubricants, and reliable. Most important is the ready availability of spare parts and servicing facilities within a reasonable distance. This last factor outweighs any initial financial advantages that may be gained from acquiring low-priced equipment of unproved quality for which servicing facilities do not exist in the country of use.

It has certainly been the East African experience that equipment bought from the developed world by the State or by private individuals, or presented by well-meaning donors, without insisting that the manufacturer at the same time establishes a spares holding and servicing agency, has soon failed. Borehole and other installations have been known to stand idle for months or even years, awaiting the arrival of a small but essential spare part. Many have, in the end, been replaced by other plants supplied by locally established agents, in whose interest it is to ensure that their reputation, and hence their business turnover, is maintained, and that their products and their back-up organisation give good service.

In the livestock areas of the arid and semi-arid zones which are remote from markets and other centres, and where boreholes and other sources of surface water or groundwater are exploited by mechanical means, plant failure can have the most serious consequences, directly on the animals and their owners and indirectly on the range potential. A grazing block with forage still intact but with a failed water supply will be underused while, inevitably, a neighbouring block with water will be at risk through overgrazing, either by premature occupancy or by the influx of more animals than it can carry. The operating water supply may also become overstrained. Where the supply is from a well or a borehole, excess pumping hours may damage the plant and also the aquifer, both of which in the end may fail totally. The argument for reliable equipment of good quality, even at extra cost, backed up by a reliable service agency within easy reach, is quite clear.

6.4.2 Power for pumping

In addition to maintenance costs, a major cost of pumping is the cost of power to operate the pump. In areas of limited economic return the efficient use of available power is of utmost importance. The types of power available are as follows:

i) *Manpower and animal power* are the oldest and, in many places, the only form of power available. Either can be completely adequate and should not be overlooked nor underestimated. From ancient times simple devices have been used for raising water which depend on human labour. More advanced devices using animal power can raise water from riverbeds or wells up to an apparent economic limit of about 9 m (Carruthers and Clark, 1981). Manpower output for water lifting, with primitive pumping, is in the range of up to 10 m^3/man-hour. Oxen tire more quickly than men, and a pair of oxen generally work only 5 hours a day. Output can be up to 70 m^3/h for a pair of oxen, depending on climate.

ii) *Gravity* is the cheapest source of power, when it is possible to use it. Considerable extra installation costs are justified for such schemes because of the significantly lower recurrent maintenance costs. Usually an economic formula can be worked out, based on the life and cost of pumping equipment as compared to the cost of a gravity pipeline.

iii) *Windpower* is another cheap source of power which should be given careful consideration for either individual or community supplies. The rising cost of petroleum has generated a renewed interest in windmills for pumping water wherever conditions are favourable.

iv) *Solar energy* is another source which is claimed to have low operating costs, a long lifetime of the equipment installed, minimum maintenance problems and no need for skilled manpower (ECA, 1976).

v) *Electricity*, if available at a reasonable cost, is to be preferred to most other systems because of the low capital and operating costs. Electric motors require very little attention and give long service.

iv) *Internal combustion engines using petroleum, diesel or kerosene*. These engines, in spite of being expensive and costly to maintain, are the most common types of power source found in the rural areas. Experience in such areas indicates that diesel engines are generally the best option, even though they are the most expensive in original cost (Wagner and Lanoix, 1959).

6.4.3 Wind energy technology

The use of wind power also has a long history. Over the centuries windmills have been used to grind corn, as in Western Europe, and to raise water, as in Crete and in other parts of the Mediterranean. From the early structures of wood and cloth or straw matting, windmills have progressed to structures of steel with elaborate gearing systems aimed at increased efficiency. More recently, wind power has been harnessed to generate electricity, and research continues on the design of windmills that can be made locally and cheaply by small-scale craftsmen without loss of quality.

However efficient a windmill may be, it still depends on the constancy and reliability of the wind. While it may not be critical if corn cannot be ground for 2 or 3 weeks because of a succession of still days, it is very critical when water cannot be pumped or electricity generated. A partial and expensive remedy then lies in the provision of storage – large surface or elevated tanks for water and large banks of batteries for electricity.

Such storage can rarely be fully satisfactory because the duration of a windless period cannot be predicted and there is a risk that the storage may be inadequate. The provision of watertight tanks above ground level represents a substantial capital outlay. A safe alternative is to duplicate the windmill with a fuel-driven pumping unit which would only be used on days with insufficient wind, but this also represents a substantial capital outlay.

In tropical Africa wind energy is not as reliable as in temperate latitudes. The eastern coastline is dominated by the monsoons which blow strongly up to about 10 km from the sea, after which they weaken and tend to be gusty. Between the monsoons there is a windless period which may last for several weeks. In the East African highlands monsoon winds penetrate, but vegetation and topography tend to decrease the surface winds. Even on the open plateaux completely windless periods of up to 6 weeks have been recorded. In hilly country the water source is usually found in the bottom of a valley where steady winds do not penetrate, and under such conditions a windmill would be completely uneconomic.

The plateaux of central tropical Africa, situated west of the Great Rift Valley, are still under the influence of trade winds which blow continuously for long periods, but they are considerably weakened away from the coast and there are still significant seasons of nearly windless days.

On the other hand, there are many areas where sufficiently high and constant wind speeds make wind power a suitable alternative energy source. Maintenance costs must be taken into account, however, and windmills require a degree of supervision to ensure that they are not damaged in periods of very high wind speeds.

Usually a limiting factor in the use of wind energy is the lack of sufficient data on wind speed and duration. Most small climatological or agrometeorology stations only record run-of-wind at 2 m above ground level. These data are insufficient to estimate wind speed and duration at the height of the rotor blades.

All systems use a rotating or oscillating collector to convert the kinetic energy of the wind stream into a primary motion which can be used to perform work. Wind energy conversion is ruled by several basic principles which determine how much can be extracted from the wind and the extraction capabilities of the various types of rotor. When a wind system rotor is placed in the free wind stream it imparts predictable changes in air pressure and velocity. As the wind stream approaches the turbine, the air pressure in the stream increases and the velocity decreases until the flow reaches the rotor plane.

As air moves against, over and through the rotor, it imparts energy to the rotor and loses pressure and speed. Further speed losses occur as the wind stream recedes from the rotor and expands in the rotor wake.

The amount of pressure and velocity change is dictated by the characteristics of the rotor; in particular its size and shape, its ability to extract energy, and the freedom of movement allowed by the systems to which it is connected.

The fact that the flow must be maintained limits the amount of energy which can be extracted. If all energy could be extracted, the wind speed behind the rotor would be zero. A balance must be maintained between the extracted energy and the energy flowing through the rotor. The optimum loss of wind speed which would occur is two thirds of the initial velocity. A 100% efficient system can extract the maximum percentage of wind power, derived from the following formula:

$$\frac{P_{max}}{A_T} = 0.593 \frac{\sigma V_o^3}{2} \quad \text{(WMO, 1981)}$$

where

P = power density
A_T = swept area of the turbine
V_o = initial wind velocity
σ = ambient air density.

The factor 0.593 is called the Betz limit or Betz coefficient.

Most high-performance systems now in use have extraction efficiencies far below their maximum in order to optimise their performance per unit cost. It is usually cheaper to extend blade length or tower height than to optimise rotor efficiency. The optimum power coefficient is approached when the speed of the blade tip is five to ten times the speed of the wind. For example, wind tunnel tests have shown, for 'ideal' rotor configurations, that maximum power coefficients of 0.42 can be obtained. This is 71% of the maximum efficiency attainable (WMO, 1981).

Major changes in the 'state-of-the-art' for small (less than 100 kW) electrical output wind systems have occurred during the past few years, including:

- the replacement of the upwind rotor with the downwind rotor;
- the emergence of the vertical-axis rotor as a major competitor to horizontal-axis machines; and
- the growing prevalence of a.c. output systems.

An important factor is also the increasing role of governments in supporting the improvement of these systems. Significant developments in mechanical output of the systems have included the production in the USA of 40 kW prototypes for electrical or mechanical output (WMO, 1981). At the same time, conventional 2 to 5 fan-type water pumps are still in production, with sales increasing.

Low technology, wind energy systems have the advantage of being easily built and maintained, using local labour resources. While their performance may be less than that of more sophisticated systems in terms of efficiency, their overall performance per unit cost may well prove superior due to the use of second-hand parts or locally available materials. (Fraenkel, 1975; WMO, 1981; Mamo and Jensen, 1981). The value of using locally available materials and labour resources cannot be overemphasised. Local availability means fewer delays and interruptions associated with obtaining spare parts, maintenance and repair services.

Modern multiblade or vertical-axis windmills have excellent performance characteristics, matching operational capability in low wind speeds (5 km/h) with reliability and minimum field maintenance requirements. Some systems allow the integration of auxilliary power units for periods of no wind.

A vertical-axis rotor design produces a gyroscopic effect which allows whole units to be post-mounted, thus eliminating the need for guide wires or expensive scaffold-type masts. Such wind pumps tend to be structurally simpler, having far fewer moving parts than fan- or propeller-type windmills.

In data-spare regions an interpolation of wind observations may not provide a reliable wind resource analysis. Often the data-sparse regions are in areas of complex terrain, and certain indirect indicators of wind energy, such as topographical situation, vegetation features and aeolian land forms, may aid the analysis.

The first requirement for the design of a wind energy system is to know the average frequency of occurrence of mean wind speed values at rotor height. It is also useful to know the vertical distribution of the mean wind speeds, or wind profile. Thirdly, maximum wind speeds need to be assessed in order to define the aerodynamic loads. Siting without knowing the wind characteristics may lead to less power output than is required.

The cost of wind power should be known to a reasonable accuracy before the decision is taken to install a wind energy system. Such an assessment also requires an accurate knowledge of wind characteristics at the site.

6.4.4 Solar energy

Tropical Africa is richly endowed with potential solar energy. Away from the highlands, which tend to generate cloud even during the dry season, much of the semi-arid zone has between 8 to 10 hours per day of bright sunshine in the dry months.

Considerable progress has been achieved in harnessing solar power, notably in West Africa where quite large solar units have been developed to produce an output of 25 kW and more. Such units require considerable technical skill to install and are still very costly. A unit developing 1 kW costs, at present, over US$ 20 000. As such, it is only justified for human supply in areas where no other cheaper possibility exists.

There are a number of solar water pumps in operation in various parts of the world. The first solar pump in Africa was installed in Dakar, Senegal, in 1968. Most units are barely 1 to 2% efficient and extremely expensive per cubic meter of water pumped, even from shallow wells. Intermittent pumps operated from solar cells have also been tried. The economics of their operation do not compare favourably to conventional energy sources, except in locations of dire need where no alternative source of power is available. The 1977 costs were in the range of US$ 10 000 to 20 000 per kW of generating capacity.

The most promising new option on the horizon for water pumping is the concentrating photovoltaic system, where costs in the range of US$ 1000 to US$ 2000 per kW were estimated in 1980 (UNITAR, 1982).

Further research into the technology of harnessing solar power continues and is aimed at reducing the capital cost, not only by using cheaper materials and turning to mass production, but also by developing a local capability for manufacturing at least some of the parts, such as the solar cells.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

The preceding sections have attempted to describe the physical factors affecting water availability and the methods employed in its development to supply livestock and their owners. No attempt has been made to deal with the associated topics of animal water needs, organisation and management of water supplies and the economics and planning of water supplies. These are dealt with by the companion reports in this series (King, 1983; Sandford, 1983).

Some important aspects of planning merit repetition in this report, however, and this concluding chapter makes recommendations principally in the two fields of planning, and operation and maintenance.

7.2 PLANNING

Planning may be defined as 'the orderly consideration of a project from the original statement of purpose through the evaluation of alternatives to the final decision on a course of action' (Linsley and Franzini, 1979). It may also include the concept of 'master planning', which attempts to assess the resources of regions, nations or river basins, and to define the optimum future growth pattern within that area, taking into account physical, technical, economic, organisational, institutional, legal and political criteria.

Planning, in the context of livestock water supplies, will usually be concerned with single projects. Nevertheless, every opportunity should be taken to make use of master planning activities for water; not only to achieve the optimum economic solutions, but also to ensure that all alternatives are considered. An unlikely alternative for a livestock project may well become an option when included in a wider context. For example, reference has already been made to the use of large multipurpose or power generation reservoirs either as direct water supplies for livestock or as river-regulating reservoirs to increase the dry-season flow.

In the field of soil and water conservation remedial measures to arrest soil erosion may be completely uneconomic in terms of a single project. Taken as a national programme to conserve water resources, however, or integrated with agroforestry projects, the required reafforestation and soil conservation measures may well attract the necessary funding.

Legal aspects are also best dealt with during master planning activities for water. Whether it be the revision of existing legislation to permit or control new developments, or legislation to conserve or protect the environment, important changes may be impossible to bring about except in the context of national or river basin planning.

Another important aspect relates to the gathering of meteorological and hydrological data. Studies and analyses of such data may be critical in the evaluation of different alternatives. Such studies may be extremely expensive in terms of a single project, but they are fully justified in terms of national programmes. Furthermore, national or basinwide hydrological analyses, which are normally carried out within master plan activities for water, may even provide predictive tools to assess the water resources of ungauged catchments and so obviate the need for detailed data-gathering exercises.

Regional groundwater resource studies will assist in optimum aquifer development. Master planning may also have a bearing on the availability of equipment of high capital cost, such as geophysical equipment and drilling rigs.

Often the first phase of a master plan is the compilation of a data inventory including meteorological, hydrological, geological and water quality data etc. The assembly, scrutiny and collation of such data banks greatly eases the task of the designer of new water supply schemes. There is often not the time, or it may be physically impossible, to assemble all existing data for a preliminary report. Incomplete or inaccurate studies may influence decisions as to whether to proceed and perhaps incur unnecessary costs, as well as expose projects to the hazard of a serious error.

It must not be thought, however, that master planning for water is the panacea for all future water supply problems. All too often, master plans are little more than catalogues of all physically feasible programmes, they have incomplete economic analyses and bear no relation to a country's economic development programme and priorities. In any case, master plans based on future growth patterns depend critically on technological advances, economic development and availability of funds. Master planning should be a dynamic process, with revision of objectives and priorities keeping pace with technical, cultural, political and economic changes.

Very few developing countries have gone beyond the initial stages of resource inventorising and technical evaluation of options. Even where an overall regional water management plan has been formulated, natural disasters (e.g. floods, droughts), worldwide economic depressions, political instability and a general lack of experience in implementing large-scale master plans for water means that 'crisis management' or political expediency takes the place of rational development.

7.3 PROJECT PLANNING PHASES

Whether individual projects are carried out within the framework of a master plan for water or separately, there are a number of phases or stages through which project planning usually passes before the final plan emerges.

Pre-planning phase. Unless available data are clearly sufficient to evaluate the resource, the hydrological analysis may be the controlling aspect of planning. If the historical data appear inadequate, steps should be taken to collect the required data as early as possible. This will involve the installation of new stations, unless regional analyses can be used, as described above.

Reconnaissance phase. This phase usually involves the technical identification and evaluation of alternatives to eliminate those projects which are clearly not feasible. The terms of reference of the next stage, the feasibility phase, are finalised at this point because of the costs involved in feasibility studies.

Feasibility phase. The feasibility study usually requires that the structural details of the options be evaluated and specified in sufficient detail to allow an accurate cost estimate of each option. This includes the economic evaluation of the benefits and costs, together with an identification of the intangible benefits or implications of a project.

Project evaluation phase. Projects are usually evaluated in economic terms, but it is important to consider the environmental implications of water resource projects and if necessary, commission an appropriate environmental impact assessment. Unfortunately, most projects are not known in sufficient detail in the pre-feasibility phases to allow detailed environmental impact assessments to be made. With important projects where the phasing of construction imposes time constraints there will be a tendency to force decisions through before a proper environmental impact assessment can be made. This should be strongly resisted since once a project has proceeded to final design there is a reluctance to withdraw, and the financial penalties of so doing tend to be weighed against any environmental consideration.

Final design. Once a decision has been taken to proceed with a particular option, the final design can be drawn up, construction drawings and bills of quantities can be prepared, and the construction plan can be finalised. It is recommended that the irrevocable instructions to proceed, by the client to the contractor, be delayed until completion of the final design because of the possibility that the more detailed design study may produce factors which affect feasibility. For this reason it is important that studies made at the feasibility stage (hydrological analyses, source yields, demand curves) should be carried out in sufficient detail to prevent erroneous evaluations.

Construction phase. The final phase is usually considered to be the construction phase, but two other important aspects should be included in the overall planning: operation and maintenance training and project monitoring.

Operation and maintenance training phase. In order to ensure that a project continues to supply water, it is vitally important to establish an appropriate operation and maintenance organisation. Very often, the best people to train the local people in operation and maintenance are those responsible for installing the equipment. There is a tendency for so-called 'turn-key' projects to be handed over to clients without adequate provision being made for training of operation and maintenance staff. This may not be so important where the client is capable of carrying out his own training programme. Where he is not, however, it might make the difference between the long life of a water supply scheme or early failure.

Project-monitoring phase. This is the most neglected aspect of planning. Ultimately, experience with completed projects forms the basis for future planning, for realistic phasing and for accurate economic forecasts. It also allows recurrent costs of operation and maintenance to be assessed. This is the most appropriate way to get a feedback of information for revision of a master plan.

Much criticism of aid programmes stems not so much from the faulty planning or faulty implementation of a project, but more from the absence of a monitoring phase. Often a timely report that a project is going wrong may be sufficient to stimulate the extra action needed to save it from failure. Rapidly changing economic conditions, climatic anomalies, political upsets and human fallibility can all change the probability of a project's success. Recognition of changing circumstances, of faulty forecasting or of the occurrence of extreme events may enable appropriate remedial action to be taken before a project becomes totally uneconomic.

7.4 SYSTEMS ANALYSIS IN PLANNING

One of the critical stages in the planning process is to evaluate the possible alternatives in order to select the best in terms of some specified criterion. The criterion most commonly used is cost but, where unquantifiable social benefits have a high priority, the least-cost solution may not be the best.

The various methods of optimisation, collectively known as systems analysis, have different applications. They can be used for single items in a project (e.g. one could optimise well diameter in relation to water demand, pump efficiency and discharge, aquifer thickness, cost of materials and water level fluctuation). They may be applied to single projects (e.g. number of each type of water supply system in an area), or to multiple projects where a large number of options is available.

An example of the use of systems analysis in water resource planning can be found in de Ridder and Erez (1977). In an integrated project for agriculture described by these authors, surface water availability was a limiting factor. The optimum solution was found to be the conjunctive use of surface water and groundwater. The authors point out that although the number of possible plans for joint use is very large, only a few are physically feasible.

With large, complex systems the number of parameters and variables becomes so large as to make optimisation impossible. In such cases, a number of solutions based on experience can be used in mathematical models to simulate actual conditions. In this way the alternative which offers the maximum net benefits can be identified.

7.5 FORECASTING PROBLEMS

One of the limitations of the systems approach is that any deficiencies in the input data or in the assumption as to the future situation will prevent determination of the true optimum (Linsley and Franzini, 1964). In this case, a range of forecast values or alternative future developments can be combined by preparing various 'scenarios' for the future. The scenario method attempts to frame the various future situations resulting both from the interaction of different factors and from the biophysical or socio-economic conditions influencing their pattern of development.

A combination of systems analysis and the scenario method will assist in identifying the optimum course of action, taking into account a range of possible future situations (UNITAR, 1982). The latter reference gives a number of guidelines for the efficient and harmonious development of water resources which complement the economic analysis.

These are:

i) to examine and weigh systematically all the factors determining the demand for water and to situate activities which require water in a wide and long perspective with respect to competition, regional environment, national strategy etc;
ii) to include in the analysis the qualitative variables, which are often more important than quantifiable variables;
iii) to verify the coherency of measures in the organisation and financing of development;
iv) to reveal the insufficiencies in available information, making a distinction in particular between indispensable information and information which is only secondary with respect to the objectives chosen, and to identify priority development actions which would not be questioned in the light of additional information;
v) to assess the sensitivity of the decisions to changes in one or other of the selection criteria, or in its relative importance, so that the water resources development programme will be better adapted to the

overall economic and social development strategy;

vi) to avoid as much as possible dangerous and irreversible situations for the future of the natural and/or socio-economic balances which exist at present or are to be created in arid areas; and

vii) to facilitate the exchange of various points of view from those people affected by and involved in the development.

It is also important to note that water resource planning, or the planning of any other activity, must not be done in isolation. In any plan, whether for a single project or for a component of a national master plan, the real constraints are rarely technical. The flow of funds or materials, the logistics of implementation and the organisational problems of establishing operation and maintenance facilities are more important, and often depend on priorities determined at the national level. The optimum plan will be one which is in phase with other development activities. The speed of implementation may not be as important as the building up of the necessary institutional framework to ensure the continuing success of a project. The least-cost solution, therefore, may not be the best option in the long run.

7.6 OPERATION AND MAINTENANCE

Possibly the two most important key factors in the operation of a supply system are 'simplicity' and 'reliability'. In tropical Africa and, indeed, in the whole of the developing world, there is a general lack of mechanical experience and technical skills. Whereas training programmes may be able to change this situation over the next 20 years, there is still a need now to install simple systems which have a minimum risk of mechanical failure and the minimum reliance on imported parts.

Reliability is a relative term, of course, and may well depend on the environment, on the pattern of use and on the measures taken to protect a water supply system against vandalism. Ultimately, these factors can be summarised under 'appropriate design'. There has been a tendency in the past for captive markets to be unable to exert the pressure on suppliers of hand pumps, for example, to modify their designs. As a result, inappropriate designs with inherently high maintenance costs have persisted in spite of strong criticism. The advent of the International Drinking Water Supply and Sanitation Decade has acted as a catalyst to designers and to manufacturers. The emphasis is now on low-maintenance systems, and manufacturers who refuse to modify their designs to meet the demands of developing countries will find that they lose the potentially huge markets.

Because of the enormous numbers of rural water supply systems which will have to be installed to meet the needs of the growing rural population, low operation and maintenance costs are essential. Most countries are looking towards community-level maintenance systems, where all appropriate repairs are done by men or women in the community who are given some basic instruction. Low-cost maintenance systems also imply that when the community-level maintenance organisation is unable to cope with a more serious problem, the next level can be brought in without enormous cost. Clearly it is much cheaper for a locally-based man on a bicycle or on a motorbicycle to make the visit rather than teams of people in high-cost vehicles from a regional maintenance centre.

7.7 RECOMMENDATIONS

The choice of methods of exploiting the water resources of an area will depend on many factors which may be culture- and case-specific. It is difficult to generalise, therefore, and possibly dangerous to emphasise only certain aspects of the whole procedure.

A number of important general points can be isolated, however, and identified as having an important impact on the success of a water supply system.

i) *Thorough surveys.* Prior to the consideration of options, a thorough survey of the physical constraints should be undertaken. This should be based on an understanding of the hydrological cycle and on the concept of probability of occurrence of particular events.

ii) *Long-range integrated planning.* The planning procedure should be as comprehensive as possible, using as many inputs and predictive tools as are available. Particular emphasis should be placed on environmental considerations (including water quality) and on the unquantifiable benefits which have a bearing on the selection of options. Wherever possible, the plan should be based on complete catchment or river basin development.

iii) *Sound design.* The key elements in design should be simplicity and reliability, with a minimum reliance on outside support for operation and maintenance.

iv) *Community participation.* Community participation should be encouraged at all levels from planning to implementation. In this way the concept of ownership can be introduced, and this increases the possibility of establishing community-based operation and maintenance facilities.

v) *Monitoring and evaluation.* At the completion of the construction phase, a planner should consider that only half of his responsibility has been discharged. The monitoring of the operation of a scheme through its early years, and the evaluation of the true costs and the criteria determining the success or failure of a scheme, are essential to the optimum long-term use of the water resources.

The concluding remarks must concern research, for, in a report dealing mainly with techniques of exploitation, little has been said about this important aspect. Although technology tends to advance much faster than its implementation in Third World countries, and although most of the problems of water resource development stem from organisational and logistical shortcomings rather than lack of technology, there are still fields of research activity which could have a major impact on the provision of water supplies. Research into the variability of climate, into more reliable predictive tools for hydrology, into the interrelationship between vegetation and hydrology in semi-arid areas, into the more efficient use of solar energy and into the use of systems analysis with complex, multi-faceted water projects, for example, are all areas which would produce high benefit-cost ratios.

Unfortunately, the world economic recession and the realisation that present implementation lags far behind that projected, if any water supply targets are to be met by the year 2000, have tended to divert already inadequate funds from research into the practical business of getting water to the people. Bearing in mind the relatively insignificant amounts of money which are required to fund water research, compared with the money wasted on projects which are based on unsound planning due to lack of accurate information, any investment in research with a clear practical application is economically sound.

Planning for the future is always full of hazards and pitfalls. The only certainty is that, with populations growing at frightening rates in Africa, there will always be a need for new ideas, new approaches and new technology to alleviate poverty, sickness and suffering.

Another neglected factor is the place of women in rural water supply schemes. Jorgensen (1982) points out that it is women who are usually responsible for the supply of water to the household. They should be involved in or made responsible for maintenance. Elmendorf (1981) reports that this has been the case in Angola, resulting in a marked decrease in the number of repairs. This is the exception rather than the rule, of course, and there are many difficulties in making women the focal point for operation and maintenance activities in societies where, traditionally, men are responsible for well defined tasks, including those which may be classed as technological. Resistance may be expected most strongly in pastoral groups where the position of women in society is relegated to a menial or subservient role.

On the other hand, responsibility for site selection and construction of water supplies is vested in women in many West African countries. Ultimately, women may be more reliable in ensuring the continued operation and maintenance of water supplies because they have a greater vested interest in their continuous operation.

Clearly, as water supply systems become simpler and more reliable, there will be less need for reliance on outside maintenance assistance. This applies equally to provision of replacement items and spare parts. Reliance on imported materials places an additional burden on the central authority responsible for maintenance. Ideally, locally manufactured spare parts should be widely available from retail outlets, as is the case with hand-pump parts in India and water taps for piped water schemes in Malawi.

As the number of water points grows, and as the population increases, thus creating additional demands, so the sheer size of the maintenance problem means that centralised organisation around a government department will not work unless responsibility for first- and second-line maintenance can be delegated to the rural communities.

At the simplest level, as with the maintenance of hand pumps, community caretakers must be trained in first-line maintenance, with additional support from area 'mechanics' who need not be part of the government system. With more sophisticated systems, such as engine-driven motorised boreholes, mechanics must be adequately trained, adequately supplied with spare parts and adequately supervised.

Communities should be encouraged to regard water supply systems as belonging to them rather than to remote organisations. This concept of ownership is critically important in avoiding vandalism, which commonly arises from frustration if water supplies break down. Petty theft of nuts and bolts to make ornaments or tools is a recurrent problem in the remoter areas. This can be partly overcome by good design, but ultimately can only be eliminated by communal action stemming from the concept of ownership.

Miller (1979), in a study of 97 village water supply schemes in seven African countries (Botswana, Cameroon, Kenya, Lesotho, Malawi, Tunisia and Zaire), found that only a small proportion of the projects studied had the responsibility for maintenance mandated to the villages, but that these water supply schemes had a significantly better performance in terms of frequency and length of breakdown. He concludes that self-help and community participation had their most powerful impact on the operation and maintenance aspects of water supply systems.

REFERENCES

Ahmad N. 1977. *Basic design considerations in back-filled dams.* UNDP/OTC Project INS-70/527, UNDP, Bandung, Indonesia.

ASCE (American Society of Civil Engineers). 1977. *Sedimentation engineering.* ASCE, New York.

Asnani G C. 1968. The equatorial cell in the general circulation. *J. Atmos. Sci.* 25: 133-134.

Australian Water Resources Council. 1974. *A compilation of Australian water quality criteria.* Dept. of the Environment and Conservation, Tech. Paper No. 7. Govt. Publ. Service, Canberra.

Ayoade J O. 1977. A preliminary study of the magnitude, frequency and distribution of intense rainfall in Nigeria. In: *Proc. Symp. on Flood Hydrology,* Nairobi 1975. TRRL Suppl. Rep. 259. Transport and Road Research Laboratory, Crowthorne, UK.

Balek J. 1977. *Hydrology and water resources in tropical Africa.* Developments in Water Science 8. Elsevier, Amsterdam.

Bannerman R R. 1973. Problems associated with development of groundwater in igneous and metamorphic rocks – a case study in Ghana. *Ground Water* 11(5): 31-34.

Barrett E C. 1974. *Climatology from satellites.* Methuen, London.

Baver L D. 1965. *Soil physics.* 3rd Edition. John Wiley, New York.

Berry G. 1964. The evaluation of Penman's natural evaporation formula by electronic computer. *Austr. J. Appl. Sci.* 15(1): 61-64.

Blackie J R. 1972. The application of a conceptual model to some East African catchments. M.Sc. thesis, Imperial College, London.

Blackie J R, Edwards K A and Clarke R T. 1979. Hydrological research in East Africa. *East Afr. Agric. For. J. 43* (Special Issue).

Blaney H F and Criddle W D. 1950. *Determining water requirements in irrigated areas from climatological and irrigation data.* Tech. Pub. 96. USDA Soil Conservation Service.

Bogdan A V and Pratt D J. 1967. *Reseeding denuded pastoral land in Kenya.* Ministry of Agriculture and Animal Husbandry, Nairobi.

Bouchet R J. 1963. Evaporation réelle et potentielle; signification climatique. *Int. Ass. Sci. Hydrol. Publ. 62.* General Assembly, Berkeley. Gentbrugge, Belgium.

British Standards Institution (BSI). 1965. *Methods of measurement of liquid flow in channels, British Standard 3680. Part 4A: Thin plate weirs and flumes.* BSI, London.

Brooks C E P and Carruthers N. 1953. *Handbook of statistical methods in meteorology.* HMSO, London.

Brutsaert W and Stricker H. 1979. An advection-aridity approach to estimate actual regional evapotranspiration. *Water Resour. Res.* 15: 443-450.

Carr D P and Underhill H W. 1974. *Simulation methods in water development.* Irrigation and drainage paper 23. FAO, Rome.

Carruthers I and Clark C. 1981. *The economics of irrigation.* Liverpool, University Press.

Chidley T R E and Keys K M. 1970. A rapid method of computing areal rainfall. *J. Hydrol.* 12: 15-24.

Chilton P J. 1983. Rural domestic supplies from groundwater – some pointers for planning from the Malawi experience. Paper presented at the Seminar on Water Master Planning in Developing Countries, January 1983. Norwegian Natural Committee for Hydrology, Bolkesjø.

Clack D C and Larson C L. 1981. Modelling infiltration: The key process in water management, runoff and erosion. In: eds Lal R and Russell E W. *Tropical agricultural hydrology.* John Wiley, Bath. pp. 433-450.

Clarke R T. 1973. *Mathematical models in hydrology.* Irrigation and drainage paper 19. FAO, Rome.

Davis S N and De Wiest R J M. 1966. *Hydrogeology.* John Wiley, New York.

DHV. 1979. *Shallow wells.* DHV consulting engineers, Amersfoort, Netherlands. Development Cooperation Information Department.

Dijon R. 1971. The search for groundwater in the crystalline regions of Africa. *Natural Resources Forum* 1 (1): 32-38.

Dooge J C I. 1965. Analysis of linear systems by means of Laguerre functions. *J. Siam Control Ser.* A2: 396-408.

Doorembos J and Kassam A H. 1979. *Yield response to water.* Irrigation and drainage paper 33. FAO, Rome.

Doorembos J and Pructt W O. 1977. *Crop water requirements.* Irrigation and drainage paper 24. FAO, Rome.

Dunne T and Ongweny G S. 1976. A new estimate of sedimentation rates on the Upper Taux River. *Kenya Geographer* 2(2).

East African Meteorological Department. 1961. *Probability maps of annual rainfall in East Africa.* East African Community, Nairobi.

ECA (Economic Commission for Africa). 1976. Problems of water resources development in Africa. United Nations Water Conference, African Regional Meeting E/CN. 14/NRD/WR/1. ECA, Addis Ababa.

Edwards K A. 1972. Estimating areal rainfall by fitting surfaces to irregularly spaced data. *In: Proceedings of the WMO/IAHS symposium on the distribution of precipitation in mountainous areas.* Vol II: 565-587.

Edwards K A. 1979. Regional contrasts in rates of soil erosion and their significance with respect to agricultural development in Kenya. In: eds Lal R and Greenland D J. *Soil physical properties and crop production in the tropics.* John Wiley, Chichester.

Edwards K A and Blackie J R. 1981. Results of the East African catchment experiments, 1958-1974. In: eds Lal R and Russell E W. *Tropical agricultural hydrology.* John Wiley, Bath. pp. 163-188.

Edwards K A, Field C R and Hogg I G G. 1979. *A preliminary analysis of climatological data from the Marsabit District in northern Kenya.* UNEP/MAB Integrated Project in Arid Lands, Tech. Report B-1, Nairobi.

Edwards K A and Rodda J C. 1970. A preliminary study of the water balance of a small clay catchment. *In: IAHS/UNESCO proceedings of the Wellington symposium.* Vol. 2, pp. 187-199.

Elderton W P. 1938. *Frequency curves and correlation.* Cambridge, England. 3rd Ed.

Elmendorf M. 1981. *Water, women and the decade.* Water and sanitation for health project. WASH Tech. Rep. 6. USAID, Washington.

Ericksson E. 1981. *Hydrochemistry: Chemical processes in the water cycle.* UNESCO Tech. Doc. in Hydrol. UNESCO, Paris.

FAO (Food and Agriculture Organisation). 1976. *Conservation in arid and semi-arid zones.* FAO conservation guide No. 3. FAO, Rome.

Findlater J. 1971. *Mean monthly air-flow at low levels over the western Indian Ocean.* Geophysical Memoirs 115. HMSO, London.

Fisher R A. 1922. On the mathematical foundation of theoretical statistics. *Philos. Trans. R. Soc. London, Ser.* A 222: 309.

Fleming G. 1969. Design curves for suspended load estimation. *Proc. Inst. Civ. Enqrs.* 43: 1-9.

Fraenkel P L. 1975. *Food from windmills.* Intermediate Technology Publications Ltd., London.

Freeze R A and Cherry J A. 1979. *Groundwater.* Prentice-Hall, Englewood Cliffs, New Jersey.

Glasspoole J. 1915. *British rainfall,* 55. London, p. 28.

Glover J and McCullock J S G. 1968. The empirical relationship between solar radiation and hours of sunshine. *Q.J.R. Meteorol. Soc.* 82:172-175.

Gommes R and Houssiau M. 1982. Rainfall variability, types of growing season and cereal yields in Tanzania. In: *Proceedings of the technical conference on climate in Africa.* WMO/OMM No. 596. World Meteorological Organisation, Geneva. pp. 312-324.

Gorham P R. 1964. Toxic algae. In: Jackson D F (ed.). *Algae and man.* Plenum, New York. pp. 307-366.

Greenland D J. 1979. Structural organisation of soils and crop production. In: eds Lal R and Greenland D J. *Soil physical properties and crop production in the tropics.* John Wiley, Bath. pp. 47-56.

Gregory S. 1969. Rainfall reliability. In: *Environment and land use in Africa.* Thomas and Whittington, Methuen, London. pp. 57-82.

Griffiths J F. 1972. *Climates of Africa.* Elsevier, Amsterdam.

Gumbel E J. 1942. On the frequency distribution of extreme values in meteorological data. *Bull. Amer. Met. Soc.* 23: 95-105.

Herbertson A J. 1905. The major natural regions. *Geogr. J.* 25: 300-312.

Hillel D. 1971. *Soil and water: Physical principles and processes.* Academic Press, New York.

Horton R E. 1933. The role of infiltration in the hydrological cycle. Trans. 14th. Ann. Meeting Am. Geophys. Un. pp. 446-460.

Hudson N. 1971. *Soil conservation.* Batsford, London.

Hutchinson P and Whalley W J. 1972. Calculation of areal rainfall using finite element techniques with altitudinal corrections. *Bull. IAHS.* 17: 259-272.

IWE (Institution of Water Engineers). 1969. *Manual of British water engineering practice.* Vol II: Engineering practice. IWE, London.

Jackson I J. 1977. *Climate, water and agriculture in the tropics.* Longman, London.

Jorgensen K. 1982. Rural water supply – the woman's rôle. *Afr. Water and Sewage.* Nov. 1982: 11-14.

Kenworthy J M and Glover J. 1958. The reliability of the main rains in Kenya. *East Afr. Agric. J.* 23: 276-72.

Kidd C H R. 1983. *A water resources evaluation of Lake Malawi and the Shire River.* UNDP/WMO Report. Project MLW/77/012. UNDP, Lilongwe, Malawi.

King J M. 1983. *Livestock water needs in pastoral Africa in relation to climate and forage.* ILCA Research Report 7. ILCA, Addis Ababa.

Koppen W and Geiger R. 1954. *Die Klimate der Erde.* Perthe, Darmstadt.

Krueger A F and Winston J S. 1975. Large-scale circulation anomalies over the tropics, 1971-72. *Mon. Weather Rev.* 103: 465-473.

Lambergeon D. 1982. Possibility of determining drought probability and using it in decision making. In: *Proceedings of the technical conference on climate in Africa.* WMO/OMM No. 596. World Meteorological Organisation, Geneva. pp. 130-145.

Lee P S, Lynn P P and Shaw E M. 1974. Comparison of multiquadric surfaces for the estimation of areal rainfall. *IAHS Hydrol. Sci. Bull.* 19(3): 303-317.

Linsley R K and Franzini J B. 1964. *Water resources engineering.* McGraw-Hill, New York.

Lloyd J W, Drennan D S H and Bennell B M. 1967. A groundwater recharge study in northeastern Jordan. *J. Instn. Water Engrs.* Paper No. 6962: 615-631.

Lockwood J G. 1972. *World climatology.* Edward Arnold, London.

Mamo Aseged and Jensen K. 1981. *Hand pumps: Research and development in water pumping technology.* Ethiopian Water Works Construction Authority/UNIDO ETH/77/013, Addis Ababa.

Manning H L. 1956. The assessment of rainfall probability and its application in Uganda agriculture. *Proc. R. Soc. London, Ser.* B 144: 460-480.

Mansfield W W. 1959. The influence of monolayers on evaporation from water storages. *Aust. J. Appl. Sci.* 10: 65-72.

Marloth R. 1904. Results of experiments on Table Mountain for ascertaining the amounts of moisture deposited from the southeast clouds. *Trans. S. Afr. Phil. Soc.* 14: 403-408.

McCulloch J S G. 1965. Tables for the rapid computation of the Penman estimate of evaporation. *East Afr. Agric. For. J.* 30: 286. 295.

Miller D. 1979. *Self-help and popular participation in rural water systems.* Development Centre of the OECD, Paris.

Minja W S M. 1982. The weather anomalies during the northern summers of 1972 and 1978. In: *Proceedings of the technical conference on climate.* WMO/OMM No. 596. World Meteorological organisation, Geneva. pp. 195-208.

Ministry of Agriculture. 1962. *African land development in Kenya, 1946-1962.* Ministry of Agriculture, Animal Husbandry and Water Resources, Nairobi.

Monteith J L. 1965. Evaporation and environment. *Symp. Soc. Exp. Biol.* 19: 205-234.

Morel-Seytoux H J and Khanji J. 1974. Derivation of an equation in infiltration. *Water Resour. Res.* 10(4): 795-800.

Nace R L (ed.). 1971. *Scientific framework of the world water balance.* UNESCO Tech. Papers Hydrol. 7. UNESCO, Paris.

Nagel J F. 1962. Fog precipitation measurement on Africa's south-west coast. *NOTOS* (Pretoria Weather Bureau). pp. 51-60.

NERC (Natural Environment Research Council). 1975. *Flood studies report* (Five volumes). NERC, Whitefriars Press, London.

NORCONSULT. 1981. *Kigoma water master plan. Vol. 7. – Hydrology.* Norconsult A.S. Consulting Engineers/Norwegian Agency for International Development, Oslo.

National Academy of Sciences. 1974. *More water for arid lands.* National Academy of Sciences, Washington D.C.

O'Donnell T. 1966. Methods of computation in hydrograph analysis and synthesis: Recent trends in hydrograph synthesis. In: *Proc. Tech. Meeting 21. Cent. Org. for Appl. Sci. Res.* Netherlands.

Penman H L. 1948. Natural evaporation from open water, bare soil and grass. *Proc. R. Soc. London, Ser.* A 193: 120-145.

Penman H L. 1952. The physical basis of irrigation control. In: *Proc. 13th Int. Hort. Cong. London,* 2: 913-924.

Penman H L. 1956. Evaporation – an introductory survey. *Neth. J. Agric. Sci.* 4: 9-29.

Penman H L. 1963. *Vegetation and hydrology.* Tech. Commun. 53. Commonwealth Bureau of Soils. Common. Agric. Bur., Farnham Royal, UK.

Philip J R. 1969. Theory of infiltration. *Adv. Hydrosci.* 5: 215-296.

Philips J. 1966. *The development of agriculture and forestry in the tropics.* Faber, London.

Pollock N C. 1968. *Africa.* University Press, London.

Powell S T. 1964. Quality of water. In: ed. Ven te Chow. *Handbook of applied hydrology.* McGraw-Hill, New York.

Prabhakar D R L. 1977. Description of current flood prediction methods in East Africa. In: *Proceedings of the Symposium on Flood Hydrology,* Nairobi 1975. TRRL Suppl. Rep. 259. Transport and Road Research Laboratory, Crowthorne, U.K. pp. 205-226.

Pratt D J and Gwynne M D. 1967. *Rangeland management and ecology in East Africa.* Hodder and Stoughton, London.

Priestley G H B and Taylor R J. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. *Mon. Weather Rev.* 100: 81-92.

de Ridder N A and Erez A. 1977. *Optimum use of water resources.* I.L.R.I., Wageningen.

Richl H. 1954. *Tropical meteorology.* McGraw-Hill, New York.

Richl H. 1965. *Introduction to the atmosphere.* McGraw-Hill, New York.

Rijks D A, Owen W G and Hanna L W. 1970. *Potential evaporation in Uganda.* Ministry of Minerals and Water Resources, Entebbe.

Rodier J A. 1977. The description of flood flows in West Africa. In: *Proceedings of the Symposium on Flood Hydrology,* Nairobi 1975. Suppl. Rep. 259. Transport and Road Research Laboratory, Crowthorne, UK. pp. 230-256.

Sandford S G. 1983. *Organisation and management of water supplies in tropical Africa.* ILCA Research Report 8. ILCA, Addis Ababa.

Schoeller H J. 1977. *Geochemistry of groundwater.* Supplement No. 3 to Groundwater Studies. UNESCO Tech. Papers Hydrol. 7. UNESCO, Paris.

Shaw E M and Lynn P P. 1972. Areal rainfall evaluation using two surface fitting techniques. *IAHS Hydrol. Sci. Bull.* 17(4): 419-433.

Stewart J B, Batchelor C H and Gunston H. 1982. Actual evaporation: Preliminary study of the usefulness of the method of estimation proposed by Brutsaert and Stricker. Report of the Institute of Hydrology. Wallingford.

Stewart J B. 1977. Evaporation from a wet canopy of a pine forest. *Water Resour. Res.* 13: 915-921.

Stromquist L. 1981. Recent studies on soil erosion, sediment transport and reservoir sedimentation in semiarid central Tanzania. In: eds Lal R and Russell E W. *Tropical agricultural hydrology*. John Wiley, Chichester. pp. 189-200.

TAMS (Tippetts – Abbett – McCarthy – Straton). 1979. *National master plan, Stage I. Vol. I – Water resources and demands.* TAMS/Kenya Government, Nairobi.

Temple P H and Rapp A. 1972. Landslides in the Mgeta area, western Uluguru Mountains, Tanzania. *Geogr. Ann. Ser. A* 54: 157-194.

Thiessen A H. 1911. Precipitation for large areas. *Mon. Weather Rev.* 39: 1082-1084.

Thom A S and Oliver H R. 1977. On Penman's equation for estimating regional evaporation. *Q.J.R. Meteorol. Soc.* 103: 345-357.

Thomas D B, Edwards K A, Barber R G and Hogg I G G. 1981. Runoff, erosion and conservation in a representative catchment in Machakos District, Kenya. In: eds Lal R and Russell E W. *Tropical agricultural hydrology*. John Wiley, Chichester.

Thompson B W. 1965. *The climate of Africa.* Oxford University Press, Oxford.

Thornthwaite C W. 1948. An approach towards a rational classification of climate. *Geogr. Rev.* 38: 85-94.

Tilren O A. 1979. *Manual on procedures in operational hydrology* (Five volumes). Norwegian Agency for International Development, Oslo.

Todd D K. 1959. *Groundwater hydrology*. John Wiley, New York.

TRRL (Transport and Road Research Laboratory). 1977. TRRL Supplementary Report 259. In: *Proceedings of the Symposium on Flood Hydrology,* Nairobi 1975. TRRL, Crowthorne, U.K.

Turc L. 1955. Le bilan d'eau des sols. Relation entre les précipitations, l'évaporation et l'écoulement. *Ann. Agron.* 5: 501-596.

UNDP/Malawi Government. 1982. *Manual for integrated projects for rural water supplies.* Dept. of Lands, Valuation and Water, Lilongwe.

UNESCO (United Nations Educational, Scientific and Cultural Organisation). 1982. UNESCO/CIEH experts meeting for the major regional project on the rational utilization and conservation of water resources in rural areas of Africa (south of Sahara). Unit of the Regional Office of Science and Technology for Africa, Dakar.

United Nations. 1976. *Problems of water resource development in Africa.* Proceedings of an African regional meeting, 20 to 24 September 1976. United Nations Publication E/CN/14/NRD/WR/1/Rev. 2.

UNITAR (United Nations Institute for Training and Research). 1982. *Alternative strategies for desert development and management.* Proc. Int. Conf., Sacramento, California. Pergamon, New York.

USGS. 1959. Flow-duration curves. In: ed. Searey J K. *Manual of hydrology. Part 2. Low-flow techniques.* Geol. Sur. Water Supply Paper 1542-A. U.S. Govt. Printing office, Washington.

U.S. Navy. 1952. *Water loss investigations: A review of evaporation theory and development of instrumentation.* U.S. Navy Electronics Laboratory. Rept. No. 195. 71 pp.

U.S. Public Health Service. 1950. *Individual water supply systems.* Joint committee on rural sanitation. Washington D.C.

Ven te Chow. 1964. *Handbook of applied hydrology.* McGraw-Hill, New York.

Wagner E G and Lanoix J N. 1969. *Water supply for rural areas and small communities.* WHO, Geneva.

Ward L. 1946. *The occurrence, composition, testing and utilisation of underground water in South Australia.* Geological Survey of South Australia, Bull. 23. Adelaide.

Webster K C. 1971. *Water resources development in Israel.* Tahal Consulting Engineers Ltd. Water Planning for Israel Ltd., Tel Aviv.

Webster C C and Wilson P N. 1966. *Agriculture in the tropics.* Longman, London.

Wenner C G. 1973. *A master plan for water resources and supplies in the Chilalo Awraja.* CADU Publ. No. 89, Asella, Ethiopia.

WMO (World Meteorological Organisation). 1974. *Hydrometeorological survey of the catchments of Lakes Victoria, Kyoga and Albert.* RAF/66/025 Technical Rep. 1. WHO, Geneva.

WMO (World Meteorological Organisation). 1981. *Meteorological aspects of the utilisation of wind as an energy source.* WMO Tech. Note 175. WMO, Geneva.

Woodhead T. 1968a. *Studies of potential evaporation in Kenya.* Water Development Department, Govt. of Kenya, Nairobi.

Woodhead T. 1968b. *Studies of potential evaporation in Tanzania.* Ministry of Lands, Settlement and Water Development, Govt. of Tanzania, Dar-es-Salaam.

World Bank. 1982. *IDA in retrospect: The first two decades of the International Development Association.* Oxford University Press, Oxford.

World Water. 1982. *Comment: Decade momentum in balance.* Special reprint of articles from *World Water* in 1981. Thomas Telford, London.

ABBREVIATIONS USED IN THE TEXT

ABS	alkyl benzine sulphonate
a.c.	alternating current
AE	actual evaporation
ASCE	American Society of Civil Engineers
BOD	Biochemical oxygen demand
cm	centimetre
COD	chemical oxygen demand
EC	electrical conductivity
EO	open-water evaporation
ET	potential transpiration
GRP	glass-reinforced polythene
hp	horsepower
h	hour
ITCZ	Intertropical convergence zone
IDWSSD	International Drinking Water Supply and Sanitation Decade
l	litre
km	kilometre
kW	kilowatt
m	metre
mg	milligram
min	minute
mm	millimetre
NERC	Natural Environment Research Council (U.K.)
NORAD	Norwegian Agency for International Development
P – A	pack-aquifer ratio
PE	potential evaporation
PE_B	local potential evaporation
PE_o	Potential evaporation as a function of radiation input, temperature and humidity.
pH	The negative logarithm of the effective hydrogen-ion concentration in gram equivalents per litre.
p.s.i.	pounds per square inch
PVC	polyvinylchloride
R_c	solar radiation
R_n	net radiation
sec	second
t	metric tonne
TRRL	Transport and Road Research Laboratory (Kenya)
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UNITAR	United Nations Institute for Training and Research
USGS	United States Geological Survey
WMO	World Meteorological Organisation
WHO	World Health Organisation

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