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ANTI-DESERTIFICATION TECHNOLOGY AND MANAGEMENT

ASSESSMENT OF WATER RESOURCES IN ARID AND SEMI-ARID REGIONS

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INTRODUCTION

A. Background

The occurrence of deserts is attributed to natural phenomena and to man's activities that degrade the land through mismanagement of the basic factors of land use systems, including soil, water and vegetation. Desertification, which has accompanied man's actions throughout history, is still proceeding, apparently at an increasing rate (UNEP 1977). The 1968 to 1972 drought in the Sahel of Africa has dramatized the problems of desert spread and focused international attention on the problem of desertification in general. The Desertification Conference (UNCOD) was convened by the United Nations in Nairobi, Kenya, from 29 August to 9 September 1977 to give impetus to national and international actions to halt the spread of deserts and reverse the process.

Despite the efforts made following the Conference, during 1978 to 1984, and despite the validity of the Plan of Action of the Conference, desertification has continued to spread and intensify in developing countries, particularly in Africa.

The Plan of Action to Combat Desertification (PACD) adopted at the Conference focused attention on arid, semi-arid and sub-humid areas which are most susceptible to desertification. The central theme of the PACD is the immediate adaptation and application of existing knowledge and improved land use, based on assessment, planning and sound management through the application of known ecological principles in areas subject to desertification. Assessment and evaluation lead to the formulation of land use plans which in turn lead to principles of correct land and water management and to practices that should characterize the major dryland livelihood systems: pastoralism, rainfed farming and irrigated agriculture (Biswas M.R. UNCOD in Retrospect).

Arid and semi-arid regions of the world cover more than one third of the land surface (UNESCO 1978). The density and productivity of vegetation in these regions are proportional to the water available and are to a great extent influenced by the management practices of land and water resources. Despite the possession of knowledge and scientific advances at hand to combat desertification, land degradation is accelerating in many arid and semi-arid regions of the world which total some 18 million km^2 in Africa, 16 million km^2 in Asia and 6 million km^2 in Australia. In Africa (Ethiopia and Somalia in the east and Senegal in the west) extensive areas that were once productive have been added to the territories of the Sahara. It was estimated that deserts expanded southward in the Sudan by 90 to 100 km in the last two decades (UNCOD 1977). New areas are being desertified in Brazil, Iran, Pakistan, Afghanistan and the Middle East. Morocco, Algeria, Tunisia and Libya are also affected. The problem of desertification in these areas is not so much a lack of water resources, but a lack of development and mismanagement of the available resources.

The PACD, with its recommendation for immediate initial action, requested UNEP to prepare, publish and distribute in co-operation with concerned United Nations bodies, teaching and management manuals on the specific topics of anti-desertification technology and management. Among the nine topics specified in the PACD was: "The Assessment of Water Resources".

Following consultation with concerned UN bodies, it was decided in view of the existence of adequate literature on the subject of water resources assessment to limit the manual called for by the PACD to a brief overview of the subject.

It is to be recalled that the United Nations Water Conference, 1977, by its Resolution on the Role of Water in Combating Desertification, considered water as one of the main factors limiting production and settlement in the drylands and that a lack of water and its development and the wasteful uses of water are fundamental causes of many problems of desertification and environmental degradation. Intensification and improvement of assessment arrangements for surface and ground-water resources are considered basic for combating desertification in arid and semi-arid regions.

The Mar del Plata Action Plan (UNWC 1977) has emphasized the need for regular and systematic collection and processing of hydrometeorological, hydrological and hydrogeological data of various water bodies to improve the management and development of water resources for developing planning strategies and to alleviate losses due to the natural hazards of droughts and floods.

The launching by the United Nations Education, Scientific and Cultural Organization (UNESCO) of the International Hydrological Decade (IHD 1965-1974), followed by the International Hydrological Programme (IHP) brought improved knowledge of the hydrological processes. Great advances were made in assessment methods of surface and ground water as a unified system. In addition to the conventional observation and assessment of precipitation, surface run-off and ground water, the Global Observation System (GOS) of the World Meteorological Organization (WMO) World Weather Watch Programme produced valuable meteorological and related environmental data for operation and research purposes. Great advances were made in developing new techniques and equipment for the assessment of water resources including: remote sensing and the use of satellites for data transmission, the use of nuclear techniques in water resource assessment, erosion and sedimentation, modelling techniques and the use of computers and improved forecasting methods.

The assessment and enhancement of ground-water resources, particularly in arid and semi-arid areas, are becoming increasingly important due to the growing dependence of these areas on ground-water resources. In drought stricken areas development of the ground-water resources is accelerating. While the traditional methods of ground-water exploration and assessment are still valid, new advanced technologies are now available, including modern advances in space and aerial photography for: geomorphological and geological analysis, geophysical techniques (radioactive and chemical), and environmental isotope analysis. All these developments have facilitated assessment of the ground-water potential and provided valuable information about the mechanism of ground-water movement, including tracing near-surface ground-water movement, infiltration of river water and lake bed leakages and loss to the sea (UNWC 1977).

B. Water in nature

The hydrologic cycle is the process through which water, driven by the sun's energy, circulates from earth to the atmosphere and back to the earth. Water moves through the cycle endlessly from the oceans to the atmosphere, as water vapour precipitates back

onto the continents and oceans The water that falls as rain on the land is evaporated into th' atmosphere directly or through the process of plant transpiration. It travels back to the oceans as surface run-off, percolates underground and eventually reaches the seas. As the oceans cover seven tenths of the earth's surface, the major part of precipitated water falls directly into the oceans and does not contribute to the potential of the water resources available for use by man. The distribution of fresh water resources in space and time over the globe and their magnitudes are characterized by great irregularities caused by climatic factors, variabilities and irregularities of the atmospheric motions governing the processes of water vapour transport, precipitation and its accumulation on the surface of the ground.

The arid and semi-arid zones of the world which cover about one third of the earth's surface area receive their waters directly from rain, or in the form of surface run-off, or from ground water transferred to it from the humid regions. The irregularities of the meteorological processes are the main causes of rainfall and stream flow variabilities from season to season and from one year to the next. Therefore, hydrological forecasting becomes extremely important in planning strategies.

The arid and semi-arid climate is characterized by a high level of incident radiation and high seasonal temperature variations, low humidity and strong winds with frequent dust storms. The rainfalls in those areas are generally sporadic and of high temporal and spatial variability, which leads to a great variability of short duration run-off and high sediment transport rates. The ground water and soil moisture in arid and semi-arid zones are subjected to relatively large moisture changes (Arid Zone Hydrology FAO).

C. Impact of human activities

Arid and semi-arid regions, in addition to their susceptibility to natural hazards, have conditions which quickly deteriorate through mismanagement of their fragile resources. Environmental degradation arising from overgrazing has been widespread in many arid and semi-arid regions. Almost 95 per cent of the land in arid and semi-arid regions is subjected to this process (UNCOD 1977). Tree felling and forest clearance for agriculture and fuel have contributed significantly to the spread of deserts. In such areas, human activities for utilization of the natural resources need to be in balance with the carrying capacity of those resources.

Improved human health, the spread of water supply and veterinary services and the increasing demand for animal products have resulted in large increases of human and animal populations in many arid and semi-arid regions in Africa, Asia and Latin America. These populations are well beyond the carrying capacities of those regions. During the later years of the 1950s, which were characterized by good water yields, herd sizes in the Sahel of Africa increased considerably. With the advent of the drought in the late 1960s, pasture ecosystems could no longer support the increase in animal population. Well points were frequently congested, resulting in the spread of the desert we are witnessing today. As a result of the increased pressure of population on scarce water resources in arid and semi-arid regions, demand and supply management presents particular difficulties in those areas. This reqkires a careful assessment of water resources and their uses and projected demands in order to ensure a proper balance in terms of supply and demand and to maintain a stable environment. Many arid and semi-arid regions are confronted with overgrazed pastureland, vanishing forests and precarious agriculture subjected to uncertain rainfalls, river flooding, drying up of surface water and depletion of ground-water resources.

"In many arid areas of the Sahel countries, for example, a relatively large water potential is often, in fact, available for development. The real problem therefore is not the lack of resources, but rather the lack of an integrated water management policy that will help to alleviate the current tragic conditions and prevent further desertification" (UNWC 1977). Such a policy can only be realized by proper assessment of water resources, uses and future demands.

D. Assessment of supply and demand

1. Assessment of supply

Assessment of water resources is a fundamental component in the planning and development of water resources. Assessment not only means the quantity of water available for different uses but also its quality and an understanding of different components of the hydrological and water resources' systems and regimes. The objective of water resources assessment is to determine the sources, extent and reliability of the supply and the characteristics of the water on which an evaluation of the possibilities for its control and utilization are to be based. The basic requirements of water resources assessment are the availability of minimum observation networks and a long-term systematic observation for adequate assessment of the different hydrological and meteorological parameters.

The techniques, procedures and standards for the collection, processing, archiving retrieval and analysis of data for water resources assessment have been the subject of a number of national and international publications and manuals. The majority have been published by WMO and/or UNESCO (e.g. Guide to Hydrometeorological Practices, WMO No.168., 4th edition, Vol. I: 1981, Vol. II: 1983). While those publications and manuals generally give the basic and fundamental techniques, procedures and standards for hydrological and hydrometeorological data collection and analysis adapted to arid and semi-arid environments are extremely important. The FAO Irrigation and Drainage Paper 37, Arid Zone Hydrology for Agricultural Development, is a useful document in this connection.

The following sections of this overview will throw more light on the characteristics of hydrological processes in arid and semi-arid zones including rainfall, evaporation and evapotranspiration, surface run-off, erosion and sedimentation and ground water, together with an overview of the methods of assessments for all these elements including field measurements and analysis of the collected data.

2. Assessments of uses and demands

An essential element in the process of planning, besides the assessment of resources, is the assessment of needs (UNWC 1977). The assessment of needs has to take into account present uses for different purposes and projected demands for the future. In arid and semi-arid zones, in particular, such an assessment is extremely critical to ensure a balanced supply/demand relationship and reconcile competition for water in water-short areas.

The assessment of uses and demands are generally made to determine the relative volumes. But the assessment of the impact of such uses and methods of control are becoming essential for the formulation of strategies for future demands and the evaluation of the resulting effects on the environment in general and the water resources in particular, both quantitatively and qualitatively. In order to project future needs, it is necessary to collect data on use, consumption and quality by type of user. The demand for water for different purposes should be estimated at different periods of time in conformity with national development goals to provide the basis and the perspective for the

planned development of available water resources (UNWC 1977). To this end, it is becoming essential to intiate action to estimate the demand for water for different purposes through organized statistics on use and consumption based on censuses, surveys and studies. This will help to identify the targets to be achieved over different periods of time. Needs of the people being served to consider are: a reasonable access to water supply, the area to be irrigated or rain-fed under different crops, industry, power and other basic water-related goods and services. A number of methodologies are at hand for assessment of uses and projected demands.

E. Institutional arrangements

In many countries of the world, water interests are divided among many agencies and bodies. Those divisions have developed historically with the increasing demands on water, the growing diversity of those demands and uses, and the nature of the sources of water, whether surface water, ground water, a lake basin or a river basin. There are numerous forces involved in water-related activities ranging from individuals to administrative, political and economic systems in the different countries and regions of the world. The increasing pressure for water has brought a new awareness and recognition of the need for a comprehensive approach to the development of land management of water resources and a strengthening of the co-ordination among the different agencies involved in water and water-related activities. In several countries, a number of patterns are evolving in the building of appropriate institutional frameworks to assure national co-ordination and the development of a national approach to water assessment, research and management. A number of models exist for achieving this national approach through the establishment of national water councils, water ministries and central agencies backed with a legal and legislative framework to ensure co-ordination and control of the resources and their use.

In arid and semi-arid areas and regions, the need for such central resource oriented institutions is vital. With regard to assessment organization, the normal practice in many countries is divided among many government organizations, but mainly between the hydrological and meteorological services. Due to the complexity of the problems in arid and semi-arid regions and the importance of conjunctive use of surface and ground water, supply demand interrelationships and land water management, the establishment of a central water resources assessment service is highly recommended. Such services will be responsible for co-ordination between existing water services and undertaking overall responsibility for the assessment of water resources, uses and environmental impacts, processing, investigations and information systems. The main functions of such services, as outlined in the Guide to Hydrometeorological Practices, WMO, No. 168, 4th edition Vol. I, 1981, could include:

(a) The establishment and supervision of hydrometeorological networks;

(b) Collection, processing and publication of basic data;

(c) Preparation of reports on water resources and uses;

(d) Preparation and dissemination of hydrological forecasts;

(e) Analysis and design studies;

(f) Research and development; and

(g) Training.

I. CHARACTERISTICS OF ARID AND SEMI-ARID ZONES

A. General

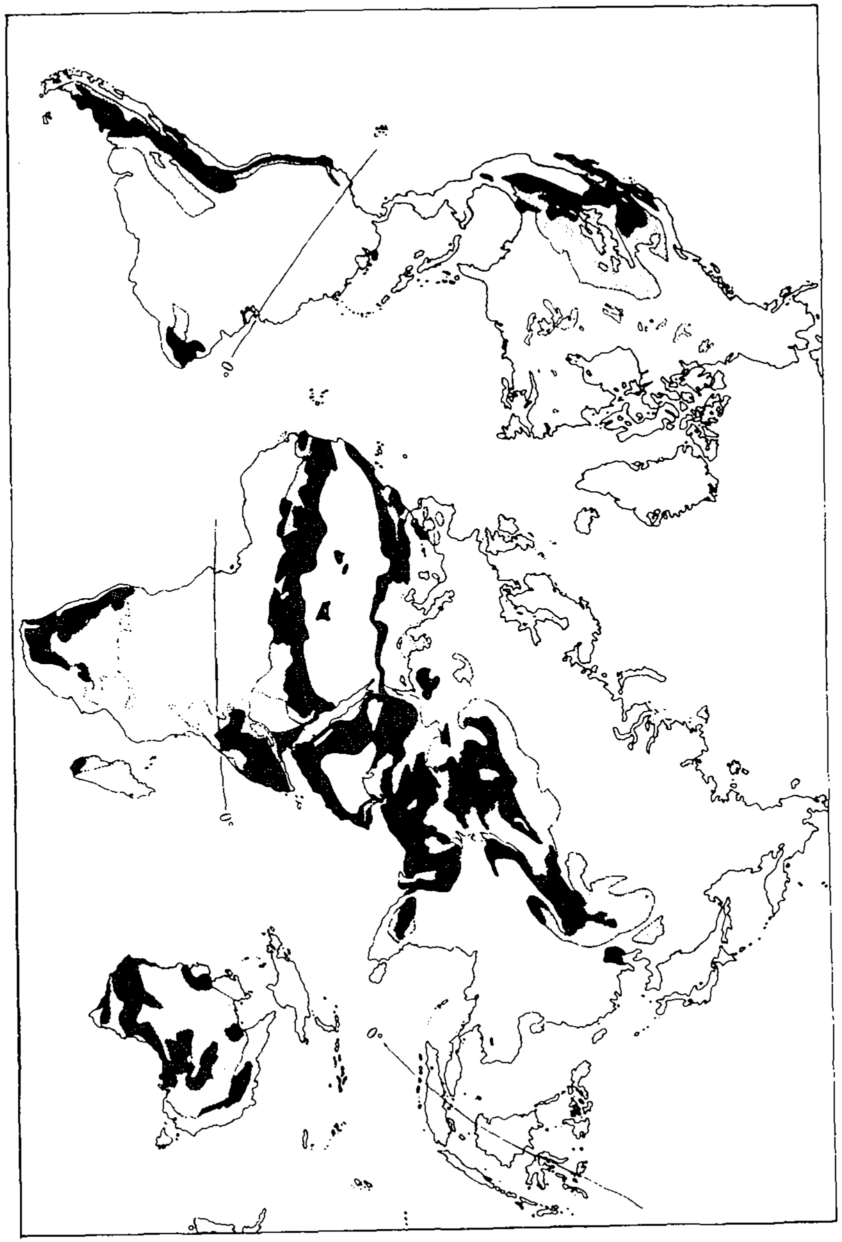
The arid and semi-arid regions of the world which cover more than one third of the land surface are roughly divided into two zones. The northern belt extends across the western part of the United States of America and Mexico, across Spain, southern France, Italy and Greece, North Africa into the Asia Minor Area, then over India and into China. The southern belt encompasses part of South America west of the Andes Mountains and the southern part of the continent and most of southern Africa and joins with the upper belt through the Arabian peninsula and India and extends south to encompass most of Australia (See World Desertification Map).

The climate in arid and semi-arid regions is characterized by an abundance of solar energy from cloudless skies, with generally high diurnal and seasonal temperature variations and annual and interannual, irregular rainfall with long dry seasons associated with strong winds. There are frequent dust and sand storms. The incoming radiation ranges from 150,000 to 200,000 cal/cm^2/year depending on the geographical location and circulation conditions of the atmosphere, which is dominated by high pressure systems with subsiding air and very little cloud for most of the year.

The soils in arid and semi-arid regions, as a result of these climatic conditions, are characterized by large variations in soil moisture, ground-water storage and high infiltration rates. A dominant feature of these soils is their susceptibility to erosion and degradation by wind, water and human activities resulting in sediment transport.

The vegetation in these regions extends outwards from the evergreen rain forests zone, covers the semi-green rain forest, savannah, the grasslands, semi-deserts and deserts and is proportional to the length of periods of water deficiency. These areas are characterized by rich fauna and high animal biomass and have great importance for agriculture, forestry and animal husbandry. The subtropical desert zones and steppe and desert with cold winters have similar problems affecting them distinct from the tropical deciduous and the savannah zones. They are characterized by low rainfall and the main difference lies in temperature. Towards their fringes, arid and semi-arid regions grade into less extreme environments, and it is particularly in these ecozones that land use problems are acute. Most of those areas in North America and Asia have been converted into the world's great grain lands.

DEGREE OF DESERTIFICATION HAZARDS
(in zones likely to be affected by desertification)



VERY HIGH ■ HIGH ■ MODERATE □

(Adapted from the United Nations Map of World Desertification, 1977)

B. Rainfall

The precipitation in arid and semi-arid regions results largely from convective cloud mechanisms and is characterized by a relatively high intensity, short duration and limited areal extent. The distribution in space is very much influenced by local terrain ranging from mountainous areas to low topographic relief. In arid lands with low ground level and little topographic relief, it is common to see rain evaporating before reaching the ground.

The dominant feature of rainfall in arid and semi-arid regions is not only its limited amount but the degree of variability in time and space. The ratio of maximum to minimum annual rainfall increases with aridity. With mean annual rainfalls of 200 to 300 mm in over 90 per cent of the record period, the rainfall ranged from 40 to 200 per cent of the mean and for 100 mm/year, 30 to 350 per cent of the mean. (See Fig. 1.) Another characteristic of arid and semi-arid zone rainfall is the direct variation of the length of the rainy season with the total rainfall amount. In the Sahel, for example, rain starts about 30 days later and ends about 20 days earlier in two years out of ten, with little correspondence between such lateness and earliness in individual years. Generally, rainfall amounts increase slowly, only early in the season, making the sowing period a precarious one because of insufficient moisture for full grain maturity (WMO special report No.9, WHO-No. 459, 1976).

The rainfall distribution in space is also very irregular, similar to its irregularity in time and as a result, neighbouring localities can have very different fortunes.

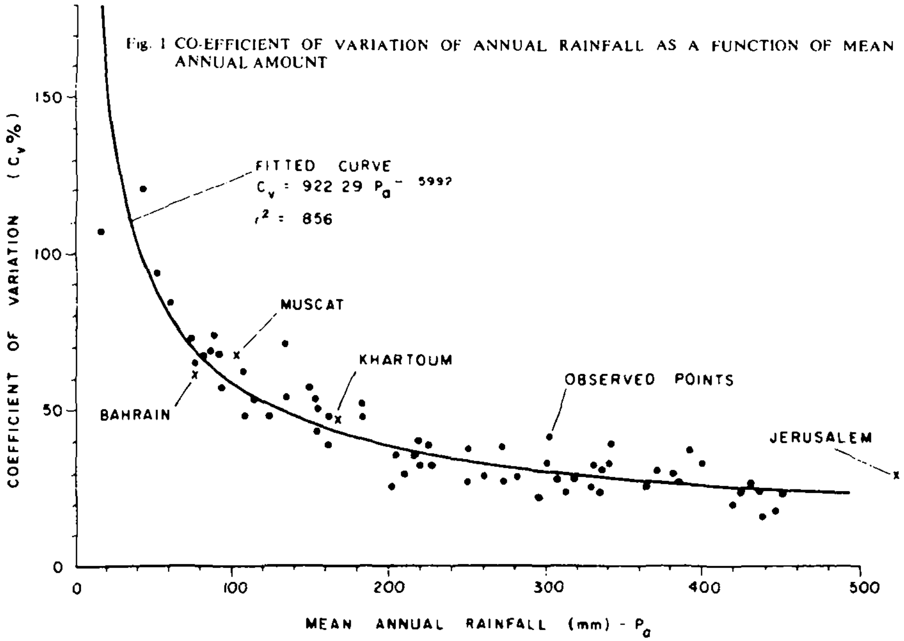


Fig. 1 CO-EFFICIENT OF VARIATION OF ANNUAL RAINFALL AS A FUNCTION OF MEAN ANNUAL AMOUNT

The data points shown in the figure each relate to a sample of gauging station records in the Near East and Nor.: Africa. The percentage co-efficient of variation (C_v per cent) of annual rainfall at a station is the standard deviation (σ) of annual totals divided by their mean and expressed as a percentage. The figure shows the greater variability of annual rainfall with decreasing mean rainfall amount at a point. C_v values for Bahrain, Muscat, Khartoum and Jerusalem are approximated reasonably well by the fitted curve.

C. Surface water resources

The surface water resources in arid and semi-arid regions result from direct rainfall or are transferred from humid regions. The patterns of flow from the first group is essentially intermittent and dry up during the rainless season. The second group have a perennial character with seasonal variations.

The run-off from direct rainfall of arid and semi-arid character has a number of sharp rises due to variation of rainstorms and is separated by periods of low or zero flows. There is no reliable relationship between seasonal or annual run-off to rainfall in arid or semi-arid regions and there is no direct relationship between the magnitude of the flood and the catchment area except in small catchments. But annual run-off shows a close relationship with the vegetation type and cover, as plant cover reduces run-off speed causing greater infiltration and loss of evapotranspiration (Fig. 2). There are of course many deviations from average relationships depending upon geological and topographical conditions and the time and space distribution of rainfall (WMO Special Environment Report No.9, No. 459, 1976). These relationships could be very useful in a comparative estimation of rainfall where flow data are available, or vice versa, as vegetation type cover can be obtained from satellite surveys.

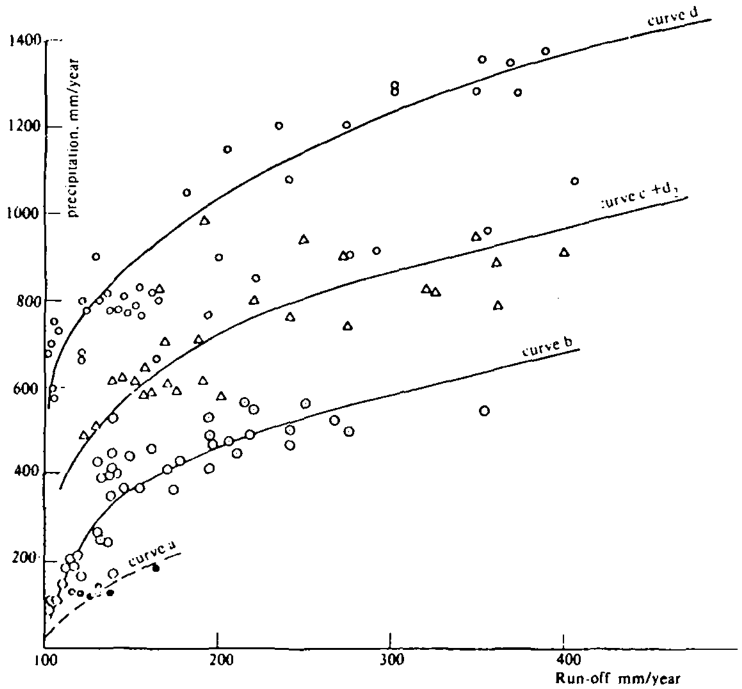


Fig. 2: RELATIONSHIP BETWEEN PRECIPITATION, TYPE OF VEGETATION AND RUN-OFF

curve a — ● : bare rock (at least 30 per cent of the basin) and steppe for the remainder of the basin

curve b — ⦿ : steppe and thorny steppe with less than 50 per cent crop fields

curve c $+d_2$ — △ : thorny steppe, arboraceous steppe and arboraceous savanna, with at least 50 per cent crop fields, and arboraceous savanna in Chad (North of 10° N)

curve d_1 — ○ : arboraceous savanna with less than 50 per cent crops (except Chad)

(Source: WMO Special Environmental Report No. 9, WMO No. 459, 1976)

The second group of run-off, transferred from humid regions to arid and semi-arid regions, is basically perennial rivers. Examples of these are the Senegal and the Nile in Africa. During their flow to the drier areas, these rivers have considerable losses to evaporation and ground water. In many arid and semi-arid regions these rivers are the main sources of water for irrigated agriculture. The perennial streams crossing these regions have extensive flood plains as they advance towards their mouths and the seasonal variations become dampened in the lower reaches.

D. Ground water

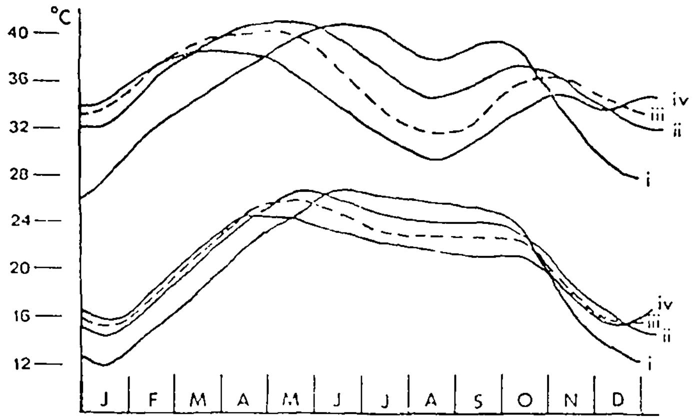
Generally, the hydrology of ground water in arid and semi-arid regions is not different from humid and temperate regions, as in the case of surface run-off. Nevertheless, in hot and cold arid regions, it has interesting characteristics and features. The main difference between the two regions is in the surface water resources that become available to the aquifer. Due to the general lack of water in arid regions, unlike wet regions, even small or poorly permeable aquifers have a very high value and therefore the estimation of the recharge and extraction becomes extremely important.

The geologic features of aquifers in arid regions are not different from those in wet regions except for minor aspects. Unconsolidated sediments of water-deposited sand and gravel and alluvial aquifers in arid valleys recharged by stream flow could still provide adequate supplies. Thick sand blown dunes in old stream channels and depressions over impermeable strata also provide useful storage as these sand formations allow considerable infiltration from local rains and their evaporation is somewhat suppressed. In hot arid regions, carbonate rocks generally are not as highly karstified as in wet regions and thus their permeability consists of relatively widespread, small solution channels which form along joints and fractures related to tectonic activity (Arid Zone Hydrology).

The hydrologic characteristics of ground water in arid and semi-arid regions including recharge, ground-water movements, discharge and change in storage and the interactions between surface and ground water are not very different from those in humid regions (UNESCO 1977). The main differences referred to in the literature include the following: The difficulty in estimating recharge in arid regions arising from irregular distribution of rainfall in space and time, the short and intermittent light run-off and the inadequacy of surface water stations.

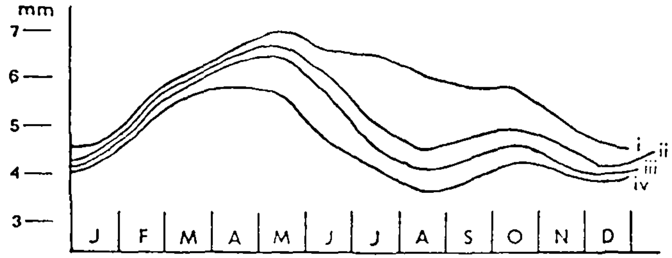
In large and extensive aquifers the problems of estimating the recharge becomes very complex. Therefore, it becomes important to determine with sufficient accuracy the geological features of the aquifer, particularly in younger volcano and carbonate rocks. As the recharge in arid regions is relatively small, the horizontal components of ground-water flow are more important than vertical movement for the determination of the hydrological balance of the aquifer. The natural ground-water discharge in arid regions appear as natural springs or disappears in streams, lakes and seas. As aridity increases, the number and discharge of springs decrease. Traditionally, populations in arid zones have interfered with aquifers by trying to deepen them to attain more discharge. This disturbance, in many instances, has resulted in the disappearance of the springs (UNESCO 1977).

Changes in ground-water storage are more variable in arid regions and depend on both the geology and hydrology of the aquifer and the determination of their storage sufficiency is difficult. Ground-water storage is most important in arid regions because it provides both seasonal carry over storage and long-term carry over storage. As the extraction exceeds recharge, the rate of water level drop will depend strongly upon storage coefficients as well as other factors (FAO Arid Zone Hydrology). It is, therefore, important that extractions be controlled to equal long-term recharge to avoid depletion of the ground water resource and avoid saline water intrusion.



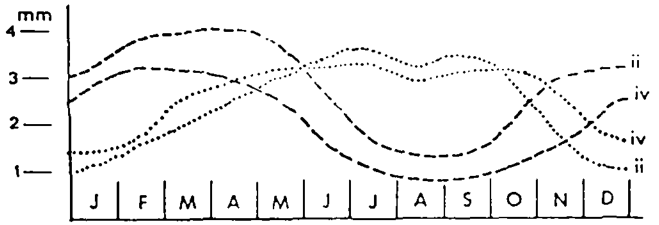
– Monthly averages of daily maximum and daily minimum temperatures in four rainfall sub-zones.

i 100-200 mm; ii 400-500 mm; iii 700-900 mm; iv 1100-1300 mm.



– Average monthly ETP mm day⁻¹ in four rainfall sub-zones.

i 100-200 mm; ii 400-500 mm; iii 700-900 mm; iv 1100-1300 mm.



– Aerodynamic and radiation terms of total ETP.

– – – – – aerodynamic .... radiation

(Source: WMO Special Environmental Report No. 9, WMO No. 459, 1976)

E. Other climatic factors

1. Day length and solar radiation

The day length in arid and semi-arid regions varies by one to two hours from winter (December) to summer (June) and from southern to northern parts of the regions which have a marked influence on patterns and varieties of crops and vegetation. Radiation varies according to the sun elevation and extent of cloud cover. In arid and semi-arid regions, both have the maximum values in the rainy season which become a limiting factor for rain-fed crops. During the dry season, with clear skies and lower sun elevation, the radiation is moderate to good for irrigated crops.

2. Temperature and evapotranspiration

Temperatures in arid and semi-arid regions vary widely from one region to another. Maximum day temperatures can reach over 40°C and the minimum generally varies between 12°C and 16°C and have significant effects on irrigated crops and the germination and growth of several tropical crops. Potential evapotranspiration and the resulting actual evapotranspiration losses to the atmosphere are high throughout the year, especially in hot summer months, and have stressing effects on germination and the establishment of young plants as a result of the rapid drying of soil moisture. Although there is little variation in maximum values of both temperature and potential evapotranspiration from one year to the next, it is notable that these elements have higher values in low rainfall years and thus aggravate crop stress in conditions of low soil moisture. (See Fig. 3.)

II. METHODS OF ASSESSMENT AND APPRAISAL OF WATER RESOURCES

A. Introduction

The old concepts and approaches for assessment of quantity and quality of water resources still remain basic. Such a simplistic and individual approach, without understanding and evaluating the complex environmental systems and natural and man-made processes and their interrelationships and interactions, will not provide the necessary data and knowledge to ensure sound development and management. An assessment of water resources, in arid and semi-arid regions, requires the formulation of strategies and plans to combat desertification and therefore need to go beyond simple hydrometeorological assessment tasks normally undertaken by the traditional hydrological services.

In arid and semi-arid zones, apart from water transferred through stream flow from humid regions, precipitation and evapotranspiration are basic elements responsible for the water resources and crop and vegetation cover in areas ranging from small catchments, to river basins, to reservoirs or lakes, to a whole region. The equation of continuity, outflow = inflow ± change in storage for any hydrological unit and specified time period is the basic concept for water balance (UNESCO 1974, Methods for Water Balance Computations). Since the change in storage becomes negligible when projected over a long period of time, the mean annual water balance for any hydrological unit becomes: Run-off = precipitation − evapotranspiration.

Therefore, the water balance concept is the basic method to estimate the hydrometeorological data. This method is applicable for any period of time, but for short periods of time the change in storage becomes important and cannot be neglected. While methods of assessing run-off, precipitation and evapotranspiration are well established by direct measurements, the assessment of the change in storage is rather complex. But it became possible by applying conceptual modelling techniques in which factors and natural laws governing the movement of water in a basin are represented by mathematical formulae. Modelling involves repetitive solutions of complex functions requiring the aid of computers. Such techniques can provide estimated daily values of several components in the hydrologic cycle and may serve many purposes. They are particularly helpful in evaluating the consequences of man's activities on water resources (UNWC 1977).

B. Assessment and appraisal of precipitation and evapotranspiration

1. Assessment of precipitation

The International Hydrological Decade (1965 to 1974) and the years that followed have produced valuable publications and a wealth of information about hydrology and related fields in the form of technical regulations, guides and manuals, technical notes and scientific reports. In the field of assessment of precipitation and evapotranspiration, reference is made in particular to the Guide to Hydrometeorological Practices (WMO No.168, 4th edition, Vol. I, 1981, Vol. II, 1983) which provided in a convenient form to all those engaged in water resources assessment, information about practices, procedures and instrumentation with references to documentation and publications on a theoretical basis and discussions on methods of application.

The chief aim of any method of measurement of precipitation should be to obtain a sample that is truly representative of the fall over the area to which the measurement refers. The requirements to achieve this should take into consideration many elements and factors including: the purpose of measurement, the quality of data to be collected, the areal variation and distribution of precipitation, the climatological and topographic features of the area, vegetation cover and population densities. Based on that information, the correct and adequate types of instrumentation can be selected, methods of observation can be defined and the design of networks formulated. The guides, manuals and literature referred to give adequate information in this respect.

Generally, in arid and semi-arid regions, the basic rain gauges network consists of daily rain gauges distributed in such a manner as to enable assessment of temporal and spatial distribution of rainfall. Totalizing (storage) rain gauges are installed in remote and uninhabited areas. Recording rain gauges are generally required in arid and semi-arid regions for the determination of the temporal characteristics of extreme variability. The field measurements of rainfall in these zones particularly aim to determine:

- rainfall, run-off recharge models;
- crop water requirements;
- point rainfall characteristics; and
- rainfall, run-off relationships.

Techniques have been developed for using radar as an aid in the measurement of rainfall. Although some quantitative determinations can be made by means of radar, its principal value is in the determination of areal extent, orientation and movement of rain storms. This method is usually used to supplement data obtained from a network of rain gauges.

2. Methods of assessment of evapotranspiration

Evapotranspiration is generally defined as transpiration and evaporation from soil, water and other surfaces. Evapotranspiration is the most difficult element to evaluate in the water balance equation. There are many techniques for computing free water evaporation and potential evapotranspiration (the maximum water loss under prevailing meteorological conditions uninfluenced by soil moisture deficiency). These techniques involve the observation of the influence of radiation, wind movement, temperature and humidity. The techniques for estimating free water evaporation are more reliable than for evapotranspiration. The accuracy of assessment in both cases can be improved with an adequate data-gathering network (UNWC 1977).

Estimates of evaporation from free water surface and the soil and transpiration from vegetation are of great importance in hydrometeorological studies, particularly in arid and semi-arid areas where evaporation losses are important for determining the feasibility of reservoirs and their operations and for water budget studies. The direct measurement from large water bodies and land surface is not possible at the present time. Evaporation pans and lysimeters have advanced and improved to give reliable results. For existing reservoirs and for plots or small catchments, estimates can be made by water budget, energy budget and aerodynamics approaches.

Evaporation from lakes and reservoirs are generally estimated by evaporation pans. Different types of pans are in use. The American class A pan and the Soviet GGI 3000 and the 20 m^2 tank are among the various types of pans in use which deserve special attention. WMO has sponsored comparative observations of these instruments in various countries. The results of the comparisons are given in the CIMO International Evaporimeter Comparisons WMO 449, 1976. The American class A pan was recommended by WMO and IASH as a reference instrument because its performance has been studied under a range of climatic conditions within quite wide limits of latitude and elevation. Auxiliary equipment with these pans include anemographs or anemometers for determining wind speeds, and rain gauges, anemometers or thermographs for air and water temperatures. Generally, in unoccupied sites particularly in arid regions, it is often necessary to protect the pans from birds and animals by the use of chemical repellents and wire-mesh.

There is no universal, international standard instrument for measuring evapotranspiration. It is generally estimated by means of soil evaporimeters and lysimeters, water or heat budget, or by the turbulent diffusion method and by various empirical formulae based on meteorological observation data. The use of soil evaporimeters and lysimeters allow the direct measurement of evapotranspiration from different land surfaces and evaporation from the soil between cultivated plants. These instruments proved to be simple and accurate enough, provided all the requirements concerning observational techniques are fulfilled.

C. Assessment and appraisal of surface water resources

All waters reaching the streams within a river basin are potentially available as surface water. As explained earlier, the patterns of the flow of these streams whose catchment areas lie wholly within arid and semi-arid zones are an integration of the physical characteristics of the drainage basin and the areal characteristics of the storms. On the other hand, there are those streams whose catchment areas lie partly outside the arid or semi-arid zones, in humid zones. These distinctions need to be taken into account when determining the assessment procedures and techniques to be followed and the type of equipment to be selected.

The WHO Guide to Hydrological Practices (WHO, No. 168, 4th edition, Vol. II, 1983) sets out, in general terms, the major objectives of a minimum network. According to the Guide, a minimum network is one which will avoid serious deficiencies in developing and managing water resources on a scale commensurate with the overall level of economic development in the country. The magnitude and frequency of floods and drought periods are of particular importance in this regard. The main problems which affect accurate data in arid and semi-arid zones includes the rapid rise and fall of discharge hydrograph, change in cross-sections during measurement, high velocities, debris and sediment loads, and difficulty in maintaining good quality, continuous water level records due to environmental factors such as waves and high sediment loads.

Improved instrumentation for measuring the flow, particularly current meters for small streams and springs and for measuring both suspended and bed load, are now available. Various types of flood height recorders for unattended measurement of peak river stages are well developed. (Guide to Hydrometeorological Practices WMO No.168, 4th edition, Vol. I, 1981, Geological Survey of Water Supply Paper 888, 1945, and many other publications.) Since the design, planning and management of water resources require knowledge of the time characteristics of flow, it is important to have a continuous record of stream-flow data for many years at points of withdrawal or use. Of course, it is rarely possible to forecast the locations for which stream-flow data will be needed in the future. Moreover, a lack of funds and trained manpower often preclude the possibility of maintaining extensive data-gathering networks. Great skill and care are required in the design and operation of basic data networks to maximize the benefits from limited expenditure. For these and other reasons, it is necessary to rely heavily on estimates. These may be derived either from measurements made at other locations or from analyses of the relationship between stream-flow and other hydrometeorological data and physiographic characteristics. Observations from similar locations may be judiciously pooled to provide better data than could be derived exclusively from any one location.

Establishment of bench-mark stations and representative catchment basins are extremely useful in the water resources assessment process. The bench-mark stations are generally established in areas uninfluenced by past or future changes. Both stations will provide climatological and hydrometeorological and other related factors to establish the interrelationships of these elements and assessment of the impact of man's influence on the environment.

Any appraisal of water supply must take economic and environmental, as well as hydrological data, into account if we are to develop plans that harmonize demand and supply within acceptable economic limits. The physical studies require frequency and sequential analyses of flow data, and should also pay heed to the availability of groundwater supplies.

Annual analysis of discharge data will yield adequate information for the planning and management of very large reservoirs and lakes. In such large reservoirs, a series of annual discharge data may permit evaluation of the possibility of critically low inflow for periods of several years. In contrast, in the case of smaller water supply reservoirs, it is necessary to know the variability of discharge within the year. And for many projects it is even necessary to consider daily discharges and possible extreme flood conditions (UNWC 1977).

Although sufficiently reliable estimates of the volume and variability of stream flow can sometimes be made by direct comparison with flow at nearby locations, it is more often necessary to use relationships between flow itself and other factors.

Hydrologists and engineers have many scientific tools and methods for assessing water supply in the absence of direct measurements. The improvement of these methods and their dissemination was the main objective of the International Hydrological Decade (1965-1974) and of the Intenational Hydrological and Operational Hydrology Programmes of UNESCO and WMO, respectively, particularly concerning the water balance (UNWC 1977).

D. Erosion and sedimentation and their appraisal and assessment

The proportion of the earth's surface affected by degradation hazards directly related to water totals about 46 per cent of the overall land area. Degradation is estimated at about 20 million km^2, and of this 22 per cent is related to water erosion (UNWC, 1977). Three basic factors influence water erosion: the climate and particularly the amount and intensity of rainfall which determine the degree of erosivity affecting the soil along with the soil properties including textural and structural qualities; infiltration characteristics and topographic features which influence the erodibility of the soil; and finally the land use practices and man's interferences including tree felling and overgrazing. In arid and semi-arid regions all these factors combine together and become a threat to land degradation and hence create suitable conditions for desert spread and general deterioration of the environment.

Sedimentation is the outcome of the erosion processes caused by precipitation and surface run-off. In arid and semi-arid regions this problem is complicated further by the action of wind.

Wind erosion and deposition are of concern in arid regions, as they alter the topography with consequent effects on infiltration and recharge, sedimentation of reservoirs and providing land surface deposits readily available to be eroded by run-off.

On the other hand, sedimentation transported by water poses numerous problems connected with reservoir storage capacities, stream flow and channel morphology. In arid zone drainage channels with beds of unconsolidated and often coarse sediments, the bed material load may play a major role behaving in the same manner as a very viscous fluid. Sediment in transport, either as bed load or in suspension, may occupy a large part of the cross-section of flow during peak flows causing spilling and considerable scouring of the channel bed. Numerous studies on river bed processes are carried out as well as compilation of data on the hydraulic and geomorphic characteristics of rivers.

The sedimentation of storage reservoirs in arid and semi-arid areas is different from those in temperate zones as the processes of sedimentation are related to high variability and seasonality of arid and semi-arid stream flows. Many countries in arid and semi-arid regions, particularly developing countries, are experiencing severe reservoir capacity depletion and short life as a result of sedimentation, particularly in small reservoirs constructed across small wadis and drainage channels for water supply. Large reservoirs for irrigation and power generation are exposed to the same problem. In Sudan, study of Khashm El Girba reservoir revealed that the reservoir lost one quarter of its capacity in seven years (Tag El Sir Ahmed Khashm El Birbe Reservoir Siltation and Silt Control Measures, Sudan Engineering Society Journal, 1971).

Sedimentation around hydraulic structures, particularly irrigation network and inlet channels for irrigation pumps, are posing serious problems in many countries in arid and semi-arid regions. Apart from the morphological changes that affect the sources of water in stream channels, the siltation of irrigation canals is a serious problem typical of arid and semi-arid regions. Apart from operational problems, it has financial implications in continuously clearing and removing the silt accumulations.

The assessment and understanding of the erosion and sedimentation processes, therefore, are essential components of the water resources assessment and an integral part of it, to control erosion particularly through sound land and water management techniques and to devise methods and design techniques to mitigate the harmful effects of sedimentation.

Within the framework of the International Hydrological Programme of UNESCO a number of projects in the field of erosion and sedimentation have been realized. These include: study of river sedimentation processes and estimation of erosion and sedimentation parameters; study of sediment generation, transport and deposition in semi-arid grasslands, development of mathematical models for sedimentation processes and predictions of sediment transport capacity of river systems; and the study of the relationship between water quality and sediment transport and methods of estimating the effects of man's activities on sedimentation processes in river basins.

The assessment and inventory of soil erosion is an essential component of the evaluation of current and potential suitability for land use alternatives. Such an assessment has been tested in many countries combining ground surveys, aerial photography and satellite imageries.

The measurement of sediment discharge and the interpretation of results are subject to great uncertainties. The existing measuring techniques and methodologies for suspended and bed load in rivers are still not satisfactory. However, there has been considerable progress in measuring techniques of sediment distribution in reservoirs. "Mathematical modelling of hydraulic and hydrological processes has progressed considerably in the past decades. The development of mathematical models for sedimentation processes would be of great benefit for study of sediment production processes, the study of the relation between solid transport, stream flow and channel morphology and the prediction of sediment inflows into reservoirs (UNWC, 1977).

The commonly used sampling techniques are to measure the discharge and obtain samples to arrive at a concentration of suspended material and to compute the suspended material from the relationship established. Two methods are used to collect samples — the equal-transit rate (ETR) and the equal-discharge increment (EDI). The ETR is generally recommended for use in arid zones. In practice the EDI method can only be applied where the rate of change of discharge permits rapid calculation of discharge distribution across the section which is not always possible in arid zones where the discharge is very erratic (Arid Zone Hydrology.)

There is quite a range of suspended load sampling equipment at hand now. The samplers in common use include: the US P-G1 Point Integrated Sampler and the US DH — 48 Depth — Integrated Sampler. Another type in use is the Nerpic Sampler which operates in either the point or depth integrating modes.

Bed load cannot be measured directly due to many factors. The rate of bed sediment movement is difficult to measure as the material moves in the form of ripples, sandbars or dunes and there are no reliable instruments at present that can be used without disturbing the stream bed and movement of the sediment. Available bed load samplers are classified into three types: basket, pan and pressure differences (Guide to Hydrometeorological Practices, WMO, No. 168, 4th edition, Vol. I, 1981).

In arid zones the bed load transported by alluvial channels is of the order of 5 to 25 per cent of suspended load. It cannot be measured satisfactorily and may therefore be accounted for only by using empirical formulae based on field and laboratory data (ASCE Sedimentation Engineering Manual).

E. Assessment of ground water

The exploration of ground water, generally speaking, has been carried out with traditional technologies i.e. geomorphological and geological reconnaissance, inventory and study of water points within every reach, and the drilling of exploratory wells. While this traditional approach still has its own validity, advanced technologies make for easier geomorphological analysis, enable less expensive and faster perforation into the ground and allow a more accurate prediction of the presence of site of ground water (UNWC 1977). These include:

1. Geomorphological and geological analysis

Modern advances in space and aerial photography have led to the improvement of geomorphological and geological analysis. Many developing countries are now using serophotographic maps as the basic data for hydrological investigations. Serographs have been used to study flat, difficult-access watersheds and to identify the only significant recharge areas of water. This will make it possible to evaluate the yearly potential and to formulate programmes for the annual exploitation of ground-water reserves.

2. Geophysical methods

Geophysical methods have been improved as a result of oil explorations. Lighter transistorized equipment is now available and the combined use of resistivity and seismotic methods is expanding. Geophysical surveys are now routinely performed in many countries before starting any drilling.

3. Ground-water movement

Radioactive and chemical tracers as well as environmental isotope analysis have provided crucial information about the mechanism of ground-water movement in many areas under diverse conditions. It is now possible to identify the most productive ground-water areas in river valleys by thermometry or to detect water losses to the sea in coastal areas by infra-red photography.

4. Ground-water models

There is a wide variety of ground-water models which have been used for ground-water studies in all climates. From the point of view of the type of ground-water model, arid regions are no different than other climates and the type of model used depends entirely on the preference, skills and resources available to the user. Kunkel (1973) presents a short discussion of data requirements for ground-water models in arid regions. While there is a very large amount of literature on ground-water models, there is no single source which gives the uninitiated guidelines on which model is best for a particular application. Instead, users tend to remain faithful to the particular kind of model they first learn about, amending it as they use it for different conditions. It is clear that, regardless of the mathematical solution used, models can be more precise in calculation than field data applied to them. Therefore, the calculation processes are no longer an issue. Pickett (1975) summarizes the types of models available.

Accuracy of data used and detail which is desired in the model will always be important issues in deciding validity of model results. One of the most obvious examples is modelling ground-water quality. It is well known that individual chemical analyses of water from nearby wells, properly collected and analysed, may fluctuate widely both in time and space. A quality model, therefore, may be mathematically precise but will not be able to duplicate complex details because geologic, hydrologic and water quality parameters may not be available with sufficient precision.

It cannot be over-emphasized that the obvious use of a model for prediction is often overshadowed in importance by use of the model simply to understand what data needs to be obtained in order to better understand the basin being studied. Ground-water models may be rather simple or they can be very complex. The more complex a model is the more data are needed. For a first attempt on a particular basin or aquifer, it may be better to resolve the problems of water balance and boundaries with a relatively simple model. The results can then be used to speed up verification of a more complex second-stage model.

F. Assessment of water uses and demands and their environmental impact

It is now fully recognized that different forms of land use affect supply availability and distribution of water resources and vice versa. Water resources development and water use or misuse affect the land resources base. But from different appraisals sponsored by UNESCO/IHP around the world, "there is no sufficient understanding of the basic relationships among precipitation, evapotranspiration water movement in the soil and water movement in the streams to permit clear-cut generalization about the effect of altering a parameter of land use or vegetation" (White 1971).

In arid and semi-arid regions, particularly in areas susceptible to desertification, the understanding of these relationships becomes extremely vital and as mentioned earlier national institutions responsible for water resources assessment need to be equipped and their capability enhanced to undertake such integrated assessment tasks and to collect the base data on demands and impact of land and water uses. The assessment of the quantities and relative volumes of water uses and prospective demands for different purposes are of particular importance, but it is equally important to also recognize the importance of assessment and appraisal of their effects and impacts. All of the multiple uses of water contribute to the vitality of human settlement, the quality of life, agriculture, industry and the social infrastructure. They vary in the degree to which they are essential to an economy and in the degree to which they affect the human environment (UNWC 1977).

"In many arid areas of the Sahel countries, for example, relatively large water potential is often, in fact, available for development. The real problem, therefore, is not the lack of water resources, but rather the lack of an integrated water management policy that will help alleviate the current tragic conditions and also prevent desertification." (UNWC 1977).

The main and most important problem in arid and semi-arid regions is how to reconcile the increasing uses of water with the fixed stock of water potentially available. To satisfy the uses and demands will determine the extent of regulation of supply and interferences in the natural flow of water. In arid and semi-arid regions the availability of water in space and time generally does not coincide with the uses and needs. The abundance of supply during wet seasons needs to be regulated, stored and transferred to meet agricultural and domestic demands during the dry season. Therefore, the assessment of these competitive uses and demands to achieve a balance between supply and demand is of vital importance.

Uses of water are classified into three types: withdrawal, in-stream and on-site. The withdrawal uses include agricultural, domestic and industrial which are of a consumptive nature. The in-stream uses include navigation, hydropower and fisheries which generally do not interfere with the volume of flow but might alter its character and may be associated with creation of storage lakes as in the case of hydropower. The on-site uses include rain-fed agriculture, rangelands and wildlife habitats which may or may not affect the volume of flow, but may influence soil moisture and evapotranspiration particularly in the case of developed crops.

All of these uses, whether consumptive or non-consumptive, may cause changes in quality of the water and other environmental hazards. The assessment of water use for irrigated agriculture will provide important information to determine the excesses or deficiencies from the real needs and enable the necessary measures to be taken to increase irrigation efficiency to prevent water logging and salinity of soils and at the same time provide a real asset for expanded use of the scarce water resources in the arid and semi-arid regions. The efficient management of water for agriculture, together with

sound land use practices, will not only conserve the water resources but also prevent soil degradation and increase productivity.

Continuous assessment of domestic uses, together with assessment of other natural resource capabilities, are of paramount importance to control desertification and depletion of water resources, particularly ground water.

The heavy human and animal population pressures on water points have, in many arid and semi-arid regions, resulted in depletion of the vegetable cover and the water resources and brought the right environment for desert spread.

The assessment of withdrawal uses for irrigation or water supply and their environmental impacts in modern systems can be made by direct measurement and observation.

In many arid and semi-arid regions in many developing countries, many patterns and forms of traditional water uses still prevail, including: terracing and cross-terracing, spate irrigation systems, and diversion of flow to cisterns for both domestic and stock watering needs. The understanding and assessment of these systems are extremely important to enable improvement of the efficiency of land and water uses and prevent flood damage.

The estimation and assessment of current uses are extremely important for demand projections to be able to ensure a balance between supply and demand. "In general, demand for water can be projected in aggregate terms based on historical relationships between per capita aggregate use and gross national product" (Hangury). The most widely used method for projecting demand is the extrapolation of a rate of use change observed over a given past time period. This method gives satisfactory results for a short-term projection of demand in areas of abundant supply. Apart from this, there are numerous analytical models that examine the factors influencing a particular use and their interrelationships including population, food consumption, farming practices technology, etc. These methods vary greatly in their sophistication and extent of the data base.

It is practicable to sketch the main features of water use and decide on the information and data needed to make a reasonable judgement and appraisal of the supply/demand situation in any area, basin or aquifer (UNWC 1977).

III. PROCESSING AND ANALYSIS OF DATA

The processing and analysis of the basic hydrometeorological data and related parameters in arid and semi-arid regions generally are not different from the regular processing procedures and methods of analysis outlined in many publications, particularly the WMO Guides to Climatological and Hydrometeorological Practices.

In arid and semi-arid areas susceptible to desertification and general environmental degradation, the processing and analysis of the basic hydrometeorological data and related parameters including land, vegetation, water uses and population interferences, need to be adjusted and reoriented to enable understanding of the complex interrelationships and interactions between all these parameters. This integrated approach is essential to evaluate not only the water potential of an area or a region, but at the same time provide valuable information to enable formulation of policies and plans to derive maximum benefits and limit the environmental harmful effects, particularly land degradation, and devise measures and actions to reverse such processes at an early stage.

Apart from the conventional processing procedure and methods of analysis for hydrometeorological data including statistical procedures (WMO Guide to Climatological Practices, WMO No. 100, 1983, and the WMO Guide to Hydrological Practices, WMO, No. 168, 4th edition, Vol. II, 1983) and mapping of elements in the hydrological balance, the use of computers to process and store the vast amounts of hydrological data and related parameters has become a general practice in many countries.

In addition to the normal analytical methods of hydrometeorological data rainfall, surface run-off, erosion and sedimentation, ground water and other related climatological data, including evaporation and evapotranspiration (WMO Guide to Hydrological Practices), should be given special attention when applying these methods to arid and semi-arid areas (FAO Arid Zone Hydrology).

In case of short historical data which is a general feature of many arid and semi-arid areas in developing countries, the use of stochastic run-off generation models is becoming a very useful tool for the analysis of arid zone run-off (Fiering and Jackson 1971 and Weiss 1977). Stochastic models have found wide recognition in studies related to the prediction of possibilities of occurrence of hydrological phenomena for modelling series of observations of precipitation and river flows and for data generation. Deterministic models which are based on cause and effect relationships are receiving more attention. They are used for defining relationships between rainfall and run-off and can stimulate the future hydrologic behaviour of watersheds when changes in watershed uses are planned. There are still many problems to be solved in modelling watershed behaviour.

Parametric modelling based on correlation and similar formulae are now widely used. There is also an increasing use of ground-water models for simulation of the consequences of ground-water withdrawal and management.

The studies undertaken by WMO/UNEP, An Evaluation of Climate and Water Resources for Development of Agriculture in the Sudano-Sahelian Zone of West Africa (Special Environmental Report No. 9, WMO, No. 459, 1976) provide guidance on analysis of climatic, hydrological and agroclimatic data for land utilization policies and for practical application for agriculture in arid and semi-arid areas.

The study of UNESCO in collaboration with FAO and WMO on practical use of results of research in representative and experimental basins could give guidance on similar works in arid and semi-arid regions. A particular reference should be made to their contributions in water resources surveys and understanding of the hydrological processes and concepts, with particular reference to the effects of man's activities on hydrological and hydrogeological processes on the environment.

The FAO *Irrigation and Drainage Paper 37, Arid Zone Hydrology*, is an extremely useful document to hydrologists and engineers working in similar areas for understanding the hydrological processes, the application of appropriate methods of measurements, evaluation, processing and analysis.

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