Committee VI
Global Environmental Problems
150

Draft-For Conference
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WORLD WATER PROBLEMS: DESERTIFICATION

by

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The Twelfth International Conference on the Unity of the Sciences
Chicago, Illinois November 24-27, 1983

INTRODUCTION

Human life is profoundly dependent on the circulation of water at the earth's surface and is very susceptible to even small deviations in the size of this flux. In technologically advanced societies such deviations affect comfort and communication: in less industrialized societies they also have important effects on the food supply and health of the population.

Over the centuries man has learnt to accept and to adapt to the large spatial and temporal variations which occur in his water supply. Indeed, the two characteristic types of extreme hydrological variations have been named after successful examples of human adaptation taken from biblical episodes - viz. Noah's evasive solution for a unique hydrological event, and Joseph's storage strategy for dealing with a sustained deviation from the norm.

Although water has always posed a major global environmental problem to man, it is the new features of this problem - those posed by the growth in human population, and the new possibilities for solutions - those made available by science and technology, that will be considered in this paper. The new aspect of the problem considered is the possibility that human activity is inadvertently affecting the hydrological cycle. Among the solutions explored are the possibility of exploiting new and reusing old water sources, and of reducing water requirements particularly in agriculture - the major consumer.

The desertification process may be considered as an extreme example of a global water problem illustrating the interaction between human and natural factors in causing the phenomenon. Both separately and in combination, man and nature have transformed large areas of useful and ecologically significant, if fragile, landscapes into desert areas, drastically reducing both their human carrying capacity and ecological diversity. Recent theories provide a biofeedback mechanism to explain how human over-exploitation of fragile semi-arid landscapes could initiate or reinforce climatic changes, strengthening and extending the desertification problem.

ADEQUACY OF WATER SUPPLY IN DIFFERENT WORLD REGIONS

The annual fluxes of precipitation and evapotranspiration over the land surfaces of the globe are shown in Fig. 1 as depths per unit land area together with the difference between the two fluxes, i.e., the potential water supply available for human exploitation.

The values, taken from Baumgartner and Reiche[1], show minima for all three quantities at the Poles. Maximum values of both precipitation and evapotranspiration occur in the equatorial region, extending over a 30°-wide latitude belt centred on the equator. Although the zone of maximum annual runoff, and the secondary maximum for precipitation, is situated considerably to the south of the equator, this region represents a negligibly small land area which is, moreover, very sparsely populated.

The equatorial zones of high hydrological activity are bounded to the north and south by the major arid and semiarid regions. These are centered around the 30° latitudes although in the northern hemisphere the vast desert and semi-desert regions of central Asia extend considerably to the north between latitudes 40° and 50°.

The reduction of hydrological activity in the mid-latitudes is made more serious by the fact that it is in these same regions that the maximum atmospheric demand for water exists. The reasons for the high potential evapotranspiration in these regions are connected with the low levels of precipitation. The associated near absence of cloud cover explains the fact that the maximum fluxes of global solar radiation are recorded in the mid-latitudes and not at the equator, as astronomical considerations would suggest.[2] At the same time, the low levels of actual evaporation ensure that most of the net radiation energy available at the surface is expended in heating the air, adding to the atmospheric water deficit and rates of air movement. Thus, aerodynamic and heat balance characteristics combine to enhance the rates of potential water demand.

The inadequacy of water supply in the mid-latitudes of the globe is greatly increased by the high interannual variability of precipitation in these regions - commonly three or more times greater than in temperate or equatorial regions. In many cases, it is this high interannual variability rather than the absolute shortage that makes this region particularly prone to desertification.

An example of this can be found in the Sahel region of sub-Saharan Africa, an area increasingly subject to desertification problems. In this area the boundaries between bioclimatic zones have generally been correlated with the values of mean annual precipitation. An isohyet of 750 mm a year has been found to correspond with the border separating the semi-humid from the semi-arid zone, 325 mm for the border between the semi-arid and arid zone, and 100 mm for the border between the arid and hyper-arid or true desert zone. However, in different regions of Africa, the isohyets corresponding to the same ecological zone boundaries were found to differ considerably from those appropriate to the Sahel. If the total annual precipitation was divided by the total annual potential water demand (calculated by Penman's combined heat balance and aerodynamic method), the resulting climatic index (developed by the Meteorological Applications group of the World Meteorological Organization) was found to be of wide general application. Values of 0.5, 0.2 and 0.06 for this index coincided with the borders separating, respectively, the semi-humid from the semi-arid, the semi-arid from the arid, and the arid from the hyper-arid zones.

Using long-term rainfall records, the standard deviation of the above climatic index was calculated for 17 stations forming three transects across sub-

Saharan Africa. The results, presented in Table 1, were used to map the areas within which the borders of the regions can be expected to lie, assuming that annual rainfall follows a normal distribution (Fig. 2).

The map shows that the northern border separating the hyper-arid from the arid zone will, for two years out of three, be found within a 200- to 100-km-wide zone, the width being least in central Africa. The border separating the arid from the semi-arid region, probably the zone at greatest risk of desertification, will be found within a zone which is 225 km wide in western Africa and 80 km wide in the upper Nile Valley. The border separating the semi-arid from the semi-humid region lies, in two years out of three, within a zone ranging in width between 225 km in the Nile Valley and 175 km at the Dahomey-Mali transect.

Thus, areas at climatic risk of desertification, and more generally those with inadequate water supply, cannot be precisely delineated in a purely spatial sense but rather should be considered as varying considerably with time, in respect to both their total area and position, within a much larger area. How large these areas are, and how they are interconnected, are important but inadequately studied aspects of the global water problem.

As an illustration of this, we may take the case of the Sahel drought of 1970-1972. During this period all three borders of the bioclimatic regions of the Sahel moved in the same southerly direction, considerably expanding the total area exposed to desertification. However, for Africa north of the equator as a whole, the expansion of the arid areas south of the Saharan desert was compensated for by a southerly movement of the borders of the arid zone north of the Sahara and by an increase north of the equator.

The redistribution of rainfall during the early 1970s which led to the Sahel and Ethiopian famines was, however, not confined to Africa. This can be seen in Fig. 3, which shows the global latitudinal deviation of rainfall from 30-year-average values. It is significant that the much larger positive deviations in precipitation to the south of the equator attracted little attention, evidently having a minor impact compared with the major effects of the smaller, negative deviations occurring in the more fragile mid-latitudes.

DESERTIFICATION AND CLIMATIC TRENDS

Recent analyses of the Sahel disaster of the early 1970s have tended to belittle the role of changing climate and attribute the famine to human mismanagement of land resources.[4] Analysis of precipitation in the Sahel region during this century has been used to support this view, for it shows that the increasing aridity experienced in the region since the 1950s falls within statistical expectations and cannot be construed as evidence of climate change.[5]

Nevertheless, desertification in the Sahel as well as similar episodes in this century in the drought-prone mid-western states of the U.S.A. and in the southern grain-growing provinces of the U.S.S.R., show a typical cyclic pattern of interaction between climate and man. During periods of benign climate coupled with advances in technology, agriculture is successfully intensified and expanded in climatically marginal regions. This leads to an increase in population density to a level which can no longer be supported when rainfall deficiencies reappear.

It has been suggested[6] that the desertification process includes an important positive feedback mechanism, whereby denudation of vegetative cover caused by overgrazing or cropping in a semi-arid zone actually inhibits rainfall, thereby reinforcing or even initiating drought. The mechanism proposed for this biodesertification process is that the reduction in vegetative cover leads to an increase in the radiative loss to space, both from the denuded surface and from the air column above it. This increased radiation loss is due primarily to the higher short wave reflectivity of bared land and to a lesser extent by their greater long wave emission caused by their higher surface temperatures. The total net radiative cooling accompanying reduced vegetation cover leads to a cooling, drying and subsidence of the air column which strongly inhibits convective precipitation.

Using realistic values of short-wave reflectivity for over-grazed and protected semi-arid areas[7], computer simulation has shown that such surface changes could reduce annual rainfall in the Sahel by 20% - a value similar to that actually recorded during the 1970-1972 drought years.[8]

Unfortunately, for reasons of scale, this theory explaining desertification as a climatic enhancement of man-initiated changes in land productivity, is hardly amenable to experimental verification and must be considered as an interesting possibility rather than a demonstrated physical explanation.

On a larger global scale, the possibility that man is inadvertently altering the climate has received much attention in recent years. The major trend emerging is a warming of the northern hemisphere, a trend especially pronounced in the upper latitudes and one predicted to exceed the "noise" level of random changes before the end of this century.

The major cause of this global warming trend is attributed to the 30% increase in the CO_2 concentration of the atmosphere which has occurred during the same period. Two human activities are thought to have been of approximately equal importance in increasing the CO_2 level. One is by the release of carbon held in the terrestrial biomass caused by deforestation and the conversion of shrub and grassland to cultivated, agricultural areas. The second way man has contributed to the CO_2 increase is now probably of much greater significance: by the release of the carbon fixed in fossil fuels during the carboniferous era.[9]

The climatic changes expected to result from the CO_2-induced warming are many and important and will almost certainly include changes in the distribution pattern of precipitation over the globe's land surfaces. Details of these changes and some of their implications for food production and other human activities are presented in another contribution to this meeting[10] and will not be considered further here.

Before leaving the question of CO_2-induced changes on water supply and demand, one important and complex physiological mechanism should be mentioned. This is the effect of increased CO_2 concentration on the size of stomatal apertures - the microscopic pores in the leaf surfaces of plants through which water vapour diffuses into the atmosphere. An increase in water vapour diffusion resistance in this pathway may be expected to follow higher levels of CO_2 concentration.[11] In regions where precipitation exceeds the climatically limited water loss, a marked decrease in water loss can be expected; in regions where the potential demand exceeds the water supply, i.e., those requiring irrigation - some compensating decrease in the rate of actual water loss and hence improvement in the water balance may also occur.

CHANGES IN THE GLOBAL WATER BALANCE AND CIRCULATION

As the volume of water on the globe - 1.4×10^9 km^3 - is essentially constant, and significant change in the current water balance and rate of its circulation can only come about through a change in the relatively small fraction of the total volume which is now in active circulation. Table 2 shows that the total annual flux through the earth's atmosphere is only 496×10^3 km^3; i.e., less than 0.03% of the total volume takes part in the annual circulation. Thus, the average residence time for water on the globe is 2800 years.

Over the ocean surface the volume of water in active circulation through the atmosphere is limited by the area of the surface exposed and the solar energy available for its vaporization. Any change in evaporation rate requires either an extraterrestrial change in the amount of solar radiation reaching the earth's atmosphere or, more probably, a change in the amount of solar energy transmitted through the atmosphere, i.e., in the degree of cloud cover or in the composition of the atmosphere.

Over the land surfaces of the globe the volume of water in circulation is dependent primarily on the precipitation. This is controlled by the pattern of atmospheric circulation and to a lesser extent by the precipitation efficiency - itself affected by aerosol composition of the atmosphere and hence influenced by human activity.

A rather weak positive feedback mechanism exists for the water circulation over the land surfaces in that a minor fraction of the precipitation is, after evaporation, reprecipitated over the same region. There is, however, one region of great significance to the biosphere where this mechanism may be important. This is the Amazon basin where as much as half of the rainfall is believed to originate from water transpired within the region.[12] As this is the Earth's major area of tropical forest in which a significant proportion of the total carbon in the biosphere is both stored and exchanged, any changes in vegetative cover affecting the rate of transpiration could, in turn, affect precipation and carbon exchange.

Measurements of changes that have taken place in the volume of water storage are available on a global scale for only one component of the water balance - the major ocean pool. A recent review of measured changes in sea levels[13] has shown that during the period between 1903 and 1969, this has increased at the rate of 15 cm per century. This century's rate of increase corresponds to the addition of 542 km^3 water volume to the oceanic pool each year - a 1.3% increase in the current annual runoff from the land to the oceans -39.7 x 10^3 km^3 (see Table 2).

There is no clear evidence as to whether the source of this increase is a melting of the polar icecaps or from a decrease in the liquid water stored on and under the land surfaces of the globe. Moreover, it should be noted that the increase in land runoff calculated from the rise in the ocean levels is less than the $\pm 2 \times 10^3$ km^3 error associated with global estimates of this term.[1]

Nevertheless, it is instructive to consider the extent to which man's current activities could be responsible for this storage change. Lvovich [14] has estimated that in 1965 man withdrew 2848 km^3 of water a year for various purposes, of which 1051 km^3 was available in return flow; the difference of 1797 km^3 presumably was lost to the atmosphere. It can be seen from the estimates presented in Table 3 that irrigation was by far the largest sink for water use by man; 2300 km^3 was estimated to have been withdrawn for this purpose in 1965, of which only 600 km^3 was available for reuse. Thus, 1700 out of the 1797 km^3 of water used by man which was not available for reuse was consumed in irrigated agriculture.

It would be reasonable to expect this large and increasing water loss to the atmosphere attributable to human activities, to reduce runoff from the land surfaces to the oceans. In one local study of changes in the water balance of an industrialized temperate region, Keller[15] showed that such a change has occurred. Nevertheless, the rise in sea level indicates that on a global scale land runoff has increased, indicating that the net effect of human activity, if responsible for this change, has been to decrease rather than increase evaporation from land surfaces.

The critical question concerning this issue is the extent to which irrigation, the major human water use, has caused a net increase in evapotranspiration compared with that from the vegetation which it has replaced. In desert areas this is almost certainly the case, but in tropical areas, where the majority of irrigated land is situated, evapotranspiration from annual irrigated crops may, in fact, be less than that from the perennial cover of natural vegetation which it has replaced.

If, globally, the net effect of irrigation has in fact been to increase water loss to the atmosphere, then this must have been more than offset by a concurrent but opposing change in the volume of water lost to the atmosphere from non-irrigated lands. This could well have come about from changes in land use, for it is well established that deforestation reduces evapotranspiration and increase runoff, as does the conversion of permanent grassland to cultivated, arable land use.[21]

A study of the effects of the large changes in land use which have taken place during this century on the regional and global water balance appears to be urgently needed to resolve this issue.

Any such study demands a global approach even if it is only the water supply to a restricted land area which is of interest. This is because ultimately the water supply depends on precipitation from the atmosphere and this, to a major degree, is derived from water which has evaporated outside the area in which it falls.

This point is illustrated by the data presented in Table 4, which contains estimates of the atmospheric water balances of different continents and regions. For the world's land surfaces as a whole, two-thirds of the water precipitated originates outside the same continental land surface on which it falls. As the global water balance given in Table 2 shows that there is a net annual flux of 40×10^3 km^3 of water from the oceans to the land surfaces via the atmosphere, the oceans clearly form a major source of this water supply.

Only in the case of the largest of the land masses, e.g. Eurasia, or in the special conditions of the Amazon basin (relatively slight air motion, tropical moist air mass), does the local contribution to precipitation reach 50%.

Thus, any major changes in the circulation of the atmosphere, or in the rate of evaporation from the oceans or to a lesser extent land areas supplying the atmosphere with water vapour, can be expected to exert a major influence on the size and distribution of the world's water supply. The speed with which such changes could be expected to occur is a function of the short residence time of water in the atmosphere - globally averaging less than 10 days, and this indicates that the length of the path over which the water cycle occurs, again averaged globally, exceeds 1000 km.

Human activities which could affect both the atmospheric circulation and the rates of evaporation have already been mentioned. To summarize very briefly, they include both man's urban and agricultural activities: the former primarily through its release of CO_2 by combustion of fossil fuels but also through the addition of aerosols, and the latter primarily through changes in land use via their effects on increasing the flux of CO_2 to the atmosphere and reducing that of water.

Perhaps the most catastrophic man-made effect on the world's water balance that can be envisaged is that which could result from a very large- scale and prolonged pollution of the ocean surfaces with an evaporation-reducing film. Even a monomolecular layer of oil could have a significant effect on the world water balance and climate if a sufficient area of ocean surface were covered for a sufficient length of time. Fortunately, the area involved would have to be very large - a 1% reduction in the water flux from the ocean to the atmosphere would, for example, require a 10% effective film covering some 30,000 km^2 of the Pacific Ocean.

ADJUSTING TO SHORTAGES AND VARIATIONS IN WATER SUPPLY

Although, for the reasons just given, the study of the world water problem and of man and climate's influence upon it demand a global approach, the practical problems of adjusting to water shortages and uncertainties in supply can be tackled usefully only within a much more restricted framework of local requirements and possibilities.

The appropriate strategy for a given locality depends very much on the use that is to be made of the water, for this will determine what solutions will be economically feasible. However, this is also strongly influenced by the general level of the local economy. For example, a farmer in western Europe can afford to pay for a piped and treated water supply for his cattle, whereas the nomadic pastoralist in the Sahel cannot afford to pay for the most minimal construciton costs to secure watering points for his family. Thus, the problem of water supply is, as for food and energy, one that must be considered within a realistic framework of economic restraints. The relevant viewpoint that will be emphasized in the following discussion is to examine the extent to which technical and scientific progress is likely to reduce the costs of existing solutions, and to develop new and more economic ones to the level at which they will be economically appropriate even in the developing areas of the world.

WATER CONSERVATION

Conservation of existing water resources, rather than the development of new ones, is certainly the preferred strategy for solving the water problems of developing territories and is particularly relevant for irrigated agriculture - the major consumer of water in such areas.

Currently, irrigation efficiency is extremely low and commonly only one-quarter or even less of the water allocated for irrigation is productively consumed by crop evapotranspiration. The remaining volume of water is, however, not merely wasted but is extremely damaging, sometimes even causing entire irrigation districts to be abandoned.

The process is a simple one - surplus water application leads to a rising water table, impeding drainage, restricting crop root development and leads to surface salinity. These factors combine to reduce crop growth and inhibit evapotranspiration, further reducing irrigation efficiency as well as yields. These problems can be ascribed to faulty design and management, which are expressed in the fact that the conveyance of water to the fields and its distribution therein are not in phase with the crop's water requirements, neither in time nor in space.

Although the reasons for the low water use efficiency of much of present day irrigation practice are well established and solutions are readily available, in practice improvements are difficult. This is not only due to the large capital sums needed to implement efficient drainage on currently cultivated land, but also because of the complex social and educational problems involved in improved irrigation practice. To arrange the even distribution of water on an individual farmer's fields at the correct time and in the correct amounts over an entire irrigation district, demands a level of community organization and cooperation that is often not available.

However, it has been shown in the United States that the water use efficiency of existing schemes can be doubled, so that over 80% of the irrigation water is used productively, without the need for replacing surface application methods with energy - and capital - intensive high-pressure systems, such as centre-pivot sprinklers and drip irrigation. The techniques used to achieve this increase in water use efficiency include the most modern, and include laser levelling of land, automatic pulsed application of water, and runoff recovery systems.[18]

Additional substantial savings in water application are possible even with correctly designed and managed irrigation systems through modification of the cropping practice. Substitution of the presently cultivated crops or varieties by ones with shorter growing seasons or those which can be grown during seasons of lower climatic water demand, can ensure substantial savings which are not matched by a proportionate reduction in yield. This is because the amount of crop growth per unit water transpired is inversely proportional to the absolute, climatically determined water requirement. The significance of this factor can be seen from some cotton irrigation experiments which showed that the same water application resulted in a 50% greater yield per unit water in the cooler and more humid coastal region of Israel than in the hotter and drier Jordan rift valley.[19]

Finally, substantial water savings are possible in arid and semi-arid irrigation farming by calculating the precise amount of water needed for the leaching requirement, i.e., that part of the application needed to wash out the soluble salts contained in the irrigation water an concentrated in the soil solution by evapotranspiration. This forms an essential part of irrigation practice in arid and semi-arid districts and is often used to justify the excessive water applications given in such regions. Relatively simple methods of calculation are now used to allow the minimum amount of water needed to prevent salinity levels in the soil building up to toxic levels.[20] In many cases the amounts so needed are only one third of those that were once applied on the basis of rule of thumb methods of calculation.

Another major aspect of water conservation in which significant savings can be made at relatively low costs concerns land use practice on the catchment areas feeding rivers, lakes, springs or underground aquifers which are eventually exploited for water wupply. Any land use practice which reduces evapotranspiration or runoff which does not contribute to the exploited sources, will increase the water supply available at a given level of precipitation.

An indication of the different levels of water yield to be expected for the two major groups of ground cover can be obtained from Fig. 4. The relationships indicate that the water yield from a catchment area receiving 700 mm of precipitation a year could be increased by as much as 1400 m^3 ha^{-1} yr^{-1} by converting a perennial woody, deep-rooted vegetation cover to a shallow-rooted, short-season grass cover.

However, the effects of land use changes are complex and changes may sometimes be counterproductive. For example, although replacing forest with closely grazed pasture will almost certainly reduce evapotranspiration and increase runoff, this latter increase may be so marked as to lead to flood and even soil erosion damage. As catchment areas are inceasingly being managed in a multi-purpose fashion, considerations other than water yield, such as recreational value, timber production or pasturage use, must also be borne in mind. Despite such limitations, there is little doubt that in some areas a substantial, sustained and economic increase in water yield from catchments can be attained by a land use management system carefully designed to meet local requirements and circumstances.

An aspect of water conservation that links the subjects of irigation practice and land use management concern efforts to reduce evaporative losses from water storage and conveyances. In many cases natural and artificial water channels and reservoirs are bordered and sometimes actually covered by perennial vegetation which unproductively transpires substantial volumes of water as well as interfering with water and other movement.

In some areas of the world, the volume of water so lost is vast. For example, the Sudd swamp region of Sudan, which covers more than 8000 km^2, is believed to evapotranspire 19 km^3 a year, at a rate of water loss that is thought to exceed that from an open water surface exposed to the same climate.[22]

To date, no simple economic method of controlling such vegetation is available and perhaps, in view of the many and as yet not fully understood effects that such changes may have, it is fortunate that any very large scale operations of this type are unlikely to be feasible before their full implications are better understood.

The above remarks also apply to the much studied question of evaporation reduction from open water surfaces. Here, again, very substantial losses occur if relatively shallow reservoirs are created in arid areas. Lake Nasser, the 500 km^2 reservoir formed by the Aswan High Dam, provides an excellent example. It has been calculated to lose 13.7 km^3 of water a year by evaporation[23], a volume considerably exceeding the amount that it has made available for irrigation.

A review of evaporation reduction studies carried out on open water surfaces[24] indicates considerable uncertainty in the efficacy of treatments now available and it has even been suggested that the deforestation involved in producing paper to report the results of such research has to date been more effective in reducing water loss[25]!

Finally, and potentially most importantly, the possibility of water conservation through treatments reducing evapotranspiration should be mentioned. Two research approaches can be distinguished. In the first, chemicals have been used to effect a reduction in the size of the stomatal apertures, thus increasing diffusive resistance to water vapour loss. To date, three main difficulties have prevented significant progress with this approach. One is the lack of an inexpensive, non-toxic, long-lasting and effective stomatal closure agent. The second difficulty is that of effectively applying the agents that do exist to reach the stomatal-bearing undersurfaces of leaves, especially in dense tree canopies. Third, and most restricting, however, are the apparently inevitable negative side effects resulting from stomatal closure. These include the reduction of carbon dioxide influx, photosynthesis, dry matter production, growth and ultimate yield that follows the increase of diffusion resistance, and also the increase in surface temperature and hence vapour concentration gradient that inevitably follows a reduction in transpiration.

The second approach for reducing plant water loss to the atmosphere attempts to increase the short-wave reflectivity of crop stands, which typically is between 0.15 and 0.25, in order to reduce the solar energy available for evapotranspiration. As this energy is reflected to outer space, the negative feedback associated with transpiration reduction by stomatal closure is avoided. However, the major difficulty - the need for an inexpensive and effective non-toxic material easily applied and long lasting - is common to the two approaches.

Field experiments with reflectant materials applied to crops growing under semi-arid conditions have failed to demonstrate any significant water conservation, although small but significant increases in yield did improve the water use efficiency.[26] In the field studies referred to, the yield response was an increase of 2 kg sorghum grain per kg kaolin clay reflectant applied at the growth stage before the seed head emerges. This yield response may be compared with that to water, which was 1.7 g per kg water evapotranspired.

The fact that the two major factors controlling plant water loss - solar energy absorption by the plant canopy and the diffusive resistance of its stomates - also control carbondioxide fixation and hence yield, explains the very high correlation between water loss and dry matter production which has been repeatedly demonstrated to apply to nearly all plant species and treatments. It is this strong coupling between H_2O efflux and CO_2 influx that makes the goal of genetic selection or engineering of new crop varieties with low water requirements and high yields such a difficult one. However, in view of the major role that irrigation farming plays in man's water requirements, and the limiting role of water in food production, this is all the more reason to regret the very minor resources currently devoted to this goal.

NEW SOURCES OF WATER

Although several methods of making sea water suitable for use have been demonstrated on a commercial scale, their cost makes the sea an uneconomic source of water except for the most essential and minor of man's requirement - his own domestic needs. Where no other water sources are available i.e., at coastal desert or island sites - the use of desalination installations has been restricted to providing the essential water needs of tourists or service personnel.

The high cost of desalinatd water can be explained by two major components - the capital cost of the material capable of withstanding sea water corrosion, and the high energy requirements needed to separate salt from water. Any substantial reduction in desalination costs are, therefore, dependent on major advances in heat exchange and corrosion technology and/or the development of new sources of cheap energy.

Occasionally claims are made that untreated sea water can be used for irrigation either directly of when diluted with less-saline sources. However, the range of soils and crops which can survive irrigation with sea water is so restricted, the yields obtained so low and the dangers of soil and aquifer salination so great, that the use of sea water in conventional agriculture is not currently of any significance. Nor does the state of research into salt tolerance of higher plants suggest that a radical change in this situation will be likey in the foreseeable future.

By contrast, some promising results are being reported from research on the culture of lower plants and animals in the sea water although this is largely restricted to organisms native to marine environments. Even in such a case, the high cost of the installations needed to cultuvate and harvest these crops has restricted land-based mariculture (sea water farming) to very high-value products, such as algae used for health food and carotene B production and sea foods such as oysters and shrimps.

The situation with regard to the use of brackish water is much more promising and large volumes of this once neglected water source are now being used in agriculture without any desalination pretreatment. Special care is of course needed to avoid the dangers of damage to the physical structure of the soil and to prevent salt accumulation to toxic levels, but both these dangers can be avoided. The techniques necessary are (a) the use of soil ameliorants - especially gypsum, (b) correct cultivation practices to avoid damage to soil structure, (c) the addition of the correct quantities of surplus water for leaching, and (d) selection of salt-tolerant crops to avoid salt accumulation in the soil.[20]

Nevertheless, some yield reductions are to be expected following irrigation with brackish water; their size depends on the degree of salinity, and to a lesser extent on the nature of the salts, an the degree of salt resistance by the crop cultlivated. The results of much research on this topic are generalized in Figure 5, based on the review of Maas and Hoffman.[27] This shows, for example, that irrigation with brackish water or moderate salinity - 8 dS m^{-1} - would not cause any reduction in the yields of tolerant crops such as barlet or cotton, whereas a moderately sensitive crop such as rice would suffer a 40% yield and a very sensitive crop such as sugar cane would not produce any yield.

It should be noted that the major advances that have permitted the large-scale use of brackish water in sustained crop reduction have resulted from agronomic research in crop, soil and water management practice rather than from an increased physiological understanding of salt tolerance or by the introduction of more salt-resistant varieties. Current progress in brackish water management using trickle or microjet application methods automatically to control the timing and placing of the irrigation water have shown that the limits of improvement obtainable by improved management practice have not yet been reached; unfortunately the cost and sophistication of these irrigation methods make them uneconomic or unsuitable for irrigated agriculture in many parts of the world.

The economic limitation to the use of desalinated sea water also applies to the reuse of domestically and industrially used waters. The capital and running costs of even the minimal treatment needed to render these sources suitable for agricultural application make reclaimed water too expensive for either the rural users or urban and industrial suppliers in all except developed countries with advanced economies.

In such areas two options are available with different costs and applications. Where the supply of fresh water is limited, complete tierciary treatment can be used to render used water suitable for reuse in every application including domestic. Although the cost of such treatment is high, there is no need for the second option, suitable where the main purpose of treatment is to prevent pollution and avoid environmental deterioration by the release of waste waters. Cheaper secondary treatments are then suitable to make the waste water suitable for agricultural use.

Care is, of course, needed to avoid health hazards and the accumulation of salts and toxic metals in crops, soils and aquifers, but there are a number of examples of successful sustained agricultures based on such waters. Indeed, the sewage water of Paris has been so used for over a hundred years.

Although the atmosphere is the smallest of the global water compartments considered dynamically, it is the only source of water to the land surfaces. Moreover, the residence time of water in its vapour from is so short that any increase in the speed of the hydrological cycle through the atmosphere would have a major effect on water supply. The potential for achieving such an acceleration is based on the rather low efficiency of the precipitation process which is, in many circumstances, limited by the number of condensation nuclei needed to initiate precipitation. In such circumstances the addition of suitable artificial nuclei from vapourized silver iodide can lead to significant increases in precipitation.

As an example of a successful and statistically clearly demonstrated result, the second Israeli randomized cloud seeding experiment may be quoted.[28] Over a period of six rainfall seasons, the average increase in precipitation achieved was 13%, at a significance level of $p = 0.028$; over the major target - the catchment of the national water carrier - the increase was 18%, $p = .017$. Much larger increases were found when the cloud top temperatures were low (-15° to -21° C) and the daily rainfall amount moderate (is less than 15 mm).

The aim of the above experiment was to improve the hydrological situation, i.e., increase the amount of precipitation contributing to the surface and underground water storage. In other situations the desired effects are more immediate and local, for example, as a form of supplementary irrigation or to improve snow conditions in resort areas.

Whatever the aim, the cost of additional water made available by a successful cloud-seeding program is very low and far less than that involved in developing most new sources or reclaiming used water.

A review of cloud seeding from the point of view of water resource management has appeared recently, and includes the topics of seeding modes and instrumentation as well as the social, legal, environmental, economic and scientific aspects of the subject.[29]

CONTROL AND REDUCTION OF DESERTIFICATION

The human factor is generally regarded as the decisive one in desertification, since, in areas at climatic risk, man's overexploitation of the natural vegetation and overcultivation of the soils will cause desertification even if precipitation and water supply are unchanged. Under natural conditions, when significant fluctuations in rainfall do occur, overexploitation during years of below-average rainfall will initiate deterioration of the natural resources even if the level of exploitation does not exceed the long-term average carrying capacity of the region.

In this sense, theoretically, the solution to the desertification problem is a simple one - the reduction of the human and animal populations to a level sustainable under the statistically expected long-term rainfall regime. Preferably this will be achieved by resettling surplus populations in underexploited regions or, if this option does not exist, by importing alternative sources of animal feed, human food and fuel, generally in that order of priority.

As the areas at risk of desertification include the poorest countries of the world, the practical possibility of resettlement or import of alternative supply is very limited. In such circumstances, the contribution that science and technology can make is also very limited. Possibaly the most important contribution is precipitation enhancement by cloud seeding in the few areas where this is likely to succeed. In other situations, it is the development of strategies that will permit the maximum sustainable carrying capacity to be maintained for the statistically most probable rainfall regime.

Estimates of this maximum rate of exploitation, together with its area, seasonal and annual variation, can be made considerably more accurate by the timely provision of adequate information on the resource status, including that of rainfall; here, remote sensing can make a large contribution. The optimum management practice also lends itself to the use of sophisticated new techniques of simulation modelling and systems analysis.

However, the major problem in controlling and reducing desertification is in the implementation of a rational program for the exploitation of natural resources by a pastoralist society. The problem is extremely complex and depressingly few successful examples are available.

In order to conclude on a more hopeful note, some of the techniques used successfully in the long desertified Negev region of southern Israel will be described briefly. The region extends from the so-called 'drought line' (corresponding to an annual rainfall of 300 mm concentrated in four mid-winter months) below which no drought compensation is available for farmers, to the extreme south and east of the region where rainfall in negligible (about 30 mm a year).

In the coastal section and at the eastern border of this extreme desert region, land use is either for tourism or very limited areas of highly intensive crop cultivation. In both cases, the favourable climate is the major natural resource and very efficient modern methods of water use are employed to make maximum use of the extremely limited amounts of underground water. The income from both tourism and the high-value out-of-season export crops produced is sufficient to pay for the import of basic foods. The system was rapidly and successfully adopted by the Bedouin inhabitants of the Sinai coastal region, and led them to reduce their livestock flocks to a minimal level serving as an insurance system.

Land use in the major part of the region has sought to maintain a maximum degree of vegetation cover to reduce soil erosion and flash floods. In the northern part of the region down to an isohyet of 200 mm a year, winter cereal cropping and improved natural pastures for lamb production have been economically successful. In the drier regions, attempts to reduce grazing of natural vegetation down to sustainable levels has proved difficult. A recent suggestion is that this limitation should be imposed by strict control of animal watering points, the capacity of which could be matched to that of the vegetation.

Perhaps the most exciting system of land use in the region is runoff farming - a combination of extensive and intensive systems of land use and one developed in the region by the Nabateans over one thousand years ago. In this system, the water runoff from a catchment area is encouraged by various forms of land treatment and utilized in contoured strips, flood plains or valley bottoms. In areas with an annual rainfall of 200 mm, experiments for the large-scale cultivation of wheat and other crops in strips separated by treated soil show promise. Further south, in the highland areas with only half this rainfall, several reconstructed Nabatean farms have produced a wide variety of crops, including orchard fruits, some for more than a decade.[30]

These few concrete examples of what has been done in a desert landscape emphasize the positive aspect of man's role in the desertification process, for they show that it is a reversible one, dependent on human will more than anything else.

TABLE 1

INTERANNUAL HYDROLOGICAL VARIABILITY IN SUB-SAHARAN AFRICA

BIOCLIMATIC REGION	STATION	COORDINATES N	COORDINATES E	NO. OF YEARS RECORD	ARIDITY INDEX* Mean	ARIDITY INDEX* Standard Deviation	Coefficient of Variation %
ARID	ABU-HAMED	19°32'	33°20'	24	.006	.008	133
	BILMA	18°41'	12°55'	20	.017	.013	75
	ATBARA	17°42'	33°58'	24	.042	.027	64
	TESSALIT	20°12'	0°59'	20	.070	.031	44
	KHARTOUM	15°36'	33°33'	24	.108	.040	37
	EL-DUEIM	13°59'	32°20'	17	.162	.048	30
	GAO	16°16'	0°03'	30	.179	.047	26
	MENAKA	15°22'	2°13'	20	.192	.048	25
SEMI-ARID	KOSTI	13°10'	32°40'	24	.259	.056	22
	SOROA	13°14'	11°59'	20	.287	.063	22
	TILLABERY	14°12'	1°27'	15	.373	.062	17
	NIAMEYA	13°29'	2°10'	27	.418	.106	25
	MADUGURI	11°51'	13°05'	54	.443	.090	20
SEMI-HUMID	MALAKAL	9°33'	31°39'	24	.500	.079	16
	GAROUA	9°20'	13°23'	20	.663	.097	15
	KANDI	11°08'	2°56'	30	.692	.115	17
	NATTINGOU	10°19'	1°23'	20	.984	.180	18

* Aridity index equals annual potential evapotranspiration divided by annual precipitation

Table 2

GLOBAL WATER BALANCE AND CIRCULATION

All values are in thousands of cubic kilometers

		Land	Oceans	Atmosphere
Total Volume		64 (+ 24 polar ice)	1,370,000	13
Annual flux	precipitation	111	385	495
	evaporation	71	425	
	runoff	40	-40	

Sources: reference (1)

Table 3

ESTIMATED WORLD WATER USE BY MAN, IN 1965 AND 2000

$km^3\ yr^{-1}$

Year	1965		2000	
Use	Withdrawal	Consumption	Withdrawal	Consumption
Irrigation	2300	1700	4250	3850
Energy	250	15	4500	270
Industry	200	40	3000	600
Urban	98	42	950	190
Total	2848	1797	12700	4910

Source: reference (14)

Table 4

ATMOSPHERIC WATER BALANCE OF THE WORLD'S LAND SURFACES - 10^3 km^3 yr^{-1}

Area	Advected	Precipitation				Evaporation
		Total	External	Local Origin	(%)	
Africa	25.0	20.0	15.0	6.0	28	16.0
Asia	21.0	26.0	17.0	8.0	32	16.0
Australia	6.0	4.0	3.0	0.65	17	3.0
Europe	9.0	6.0	3.0	1.0	19	3.5
North America	15.0	14.0	10.0	3.0	25	9.0
" (reference 17)	14.0	12.0	8.8	3.2	27	10.0
South America	30.0	24.0	18.0	6.0	24	15.0
Arizona	0.309	0.036	0.034	0.002	6	0.036
European Russia	5.4	2.4	2.1	0.3	11	1.4
U.S.S.R.	12.0	12.0	9.0	3.0	26	7.0
Eurasia	23.0	32.0	21.0	11.0	34	20.0

Sources: references (16) and (17)

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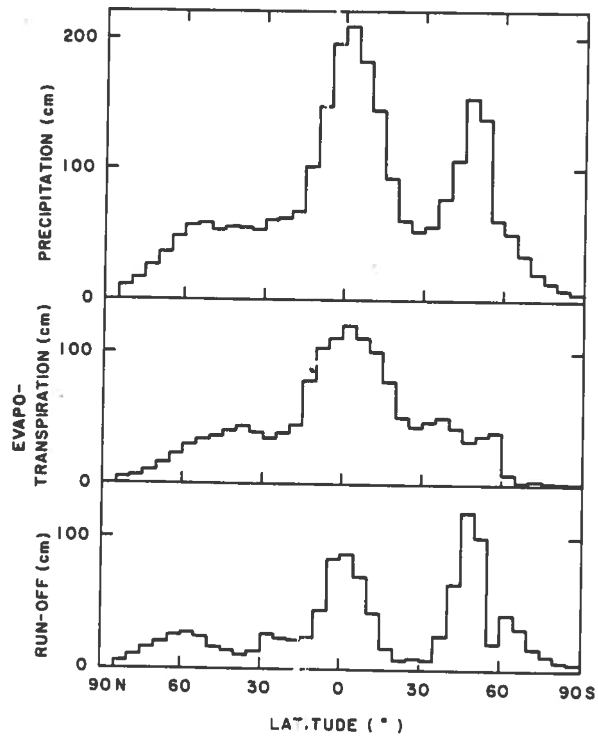

Fig. 1 The distribution of precipitation and evapotranspiration, and their difference - runoff-over the land surfaces of the globe. All values are in cm water depth equivalent per year and are taken from Baumgartner and Reichel.[1]

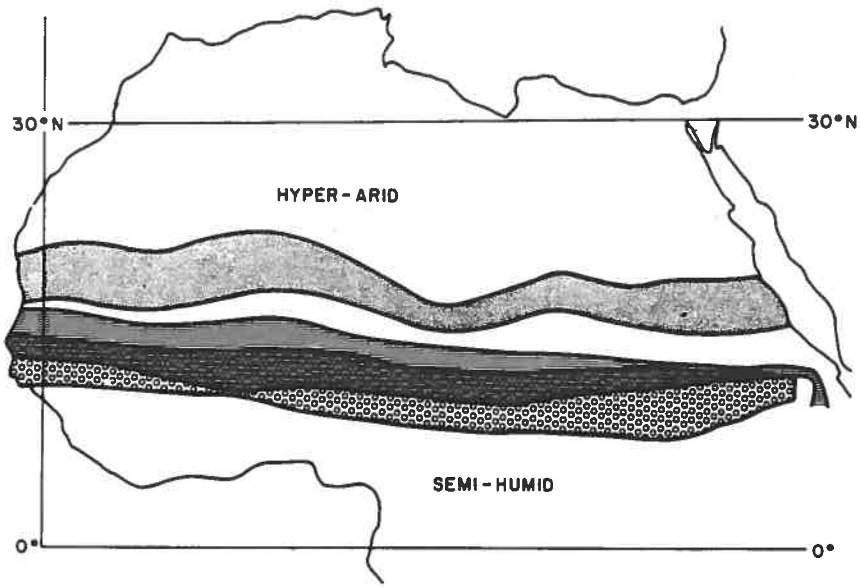

Fig. 2 Zones within which the borders between the hyper-arid, arid, semi-arid and semi-humid ecological regions can be expected to fall during two out of three years in sub-Saharan Africa.

Border zone between hyper-arid and arid regions; annual precipitation divided by annual evapotranspiration - 0.06.

Border zone between arid and sem-arid regions; annual precipitation divided by annual evapotranspiration - 0.20.

Border zone between semi-arid and semi-humid regions; annual precipitation divided by annual evapotranspiration - 0.50.

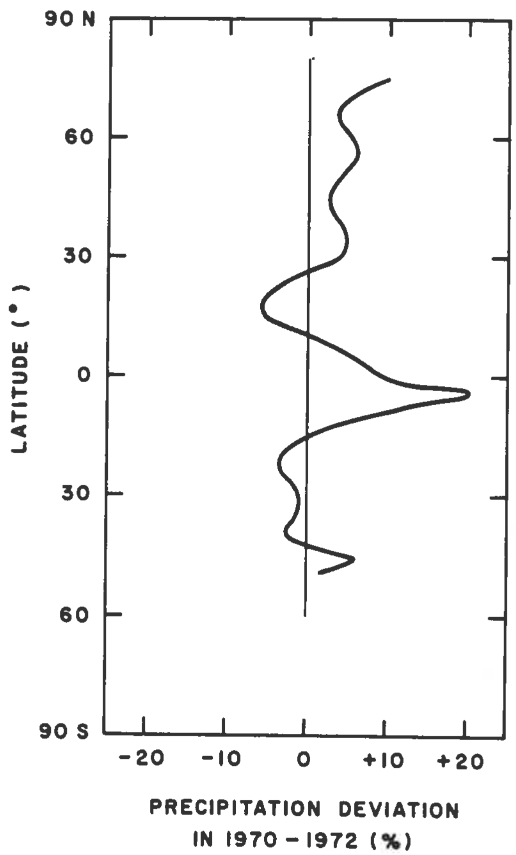

Fig. 3 The distribution of precipitation deviations during the period 1970-1972 averaged meridionally over the earth's surface. All values are in % deviations from the 1931-1960 30-year average, and are taken from Lamb.[3]

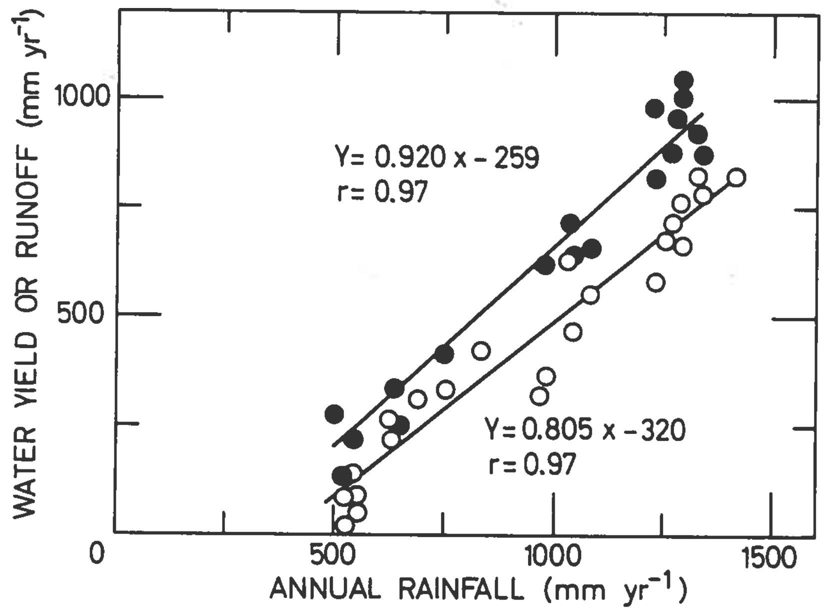

Fig. 4 Relationship between annual water yield and precipitation for two land-use practices: each point represents the result of a paired catchment study reviewed by Shachori and Michaeli.[21] The lines refer to the equations fitted by a lined regression model.
Forest, woodland or maquis scrub cover.
Grass or bare ground cover.

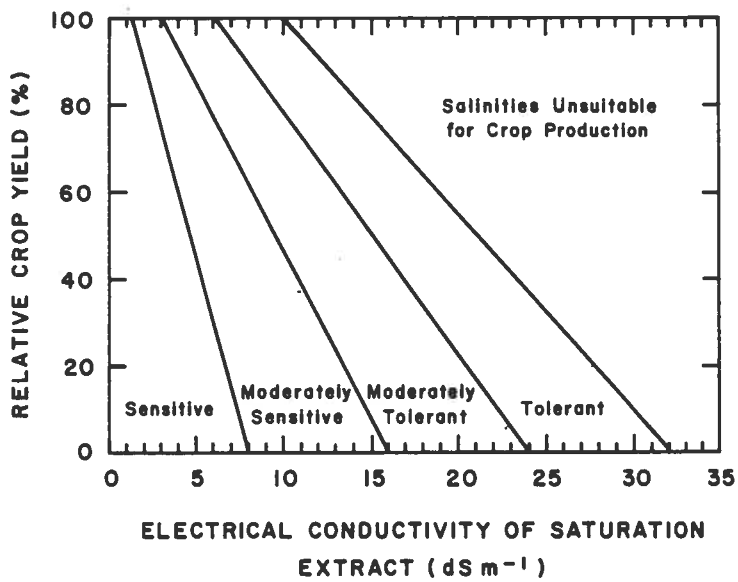

Fig. 5 Relative crop yield as a function of the salinity in the root zone from which two-thirds of the water uptake occurs and crop type. Based on review by Maas and Hoffman.[27]