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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Irrigation in Arid Lands [and Discussion]

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Irrigation in arid lands

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[Plate 1]

The positive aspects of the high irrigation demand characteristic of arid lands are reviewed, together with the classic dangers of salinization and impeded drainage common to such regions. Both aspects are illustrated by case studies of two very different arid zone demand – irrigation agricultures – those of Egypt and Israel. Atmospheric, crop, soil, hydrologic, and economic factors determining irrigation demand in arid lands are reviewed, with emphasis on the recent developments which have resulted in increased productivity and reduced water application. Finally, a brief account is given of current research which could allow these new techniques to be economically adopted on a much wider scale in the future.

Of the four elements essential for agriculture, three are present in abundance in the warm arid lands: air, ubiquitously; earth, one sixth of whose area, classified by Koppen as warm desert, is now largely unused although much is potentially suitable for cultivation; while fire, under its aspects of solar irradiance and air temperature, reaches its highest global values in these regions largely owing to the absence of the fourth essential, and limiting, element, water.

Positive and negative aspects of arid land irrigation

The distribution of atmospheric water supply over the land surfaces of the earth shows a marked decrease in the mid-latitudes centred on 30° north and south of the equator. This deficit is accentuated when the difference between atmospheric demand and supply is considered (shaded areas in figure 1). The same arid latitudes that exhibit the maximum values of water requirement are also characterized by maximum levels of potential dry matter production as a result of the high annual sums of solar irradiance recorded in these regions. Moreover, the seasonal distribution of irradiance and air temperature allows a very extended growing season – in many cases a full year long – if irrigation water is supplied.

The high potential productivity of irrigated agriculture in arid lands has been realized intermittently throughout recorded history, and admiring reports by visitors from temperate lands can be found in the classical writings. A quantitative survey of the productivity of traditional irrigated agriculture in Egypt was included in the survey of Napoleon's savants in 1800 who, on the basis of the relative yields of the wheat crop, declared this to be more than twice that of France (Girard 1812). On the basis of food energy produced per unit cultivated area, this difference has now doubled (Stanhill 1984).

Not only is irrigated agriculture in arid lands highly productive, but its productivity is also very stable, at least over short periods of time. This is because the crop yields are not subject

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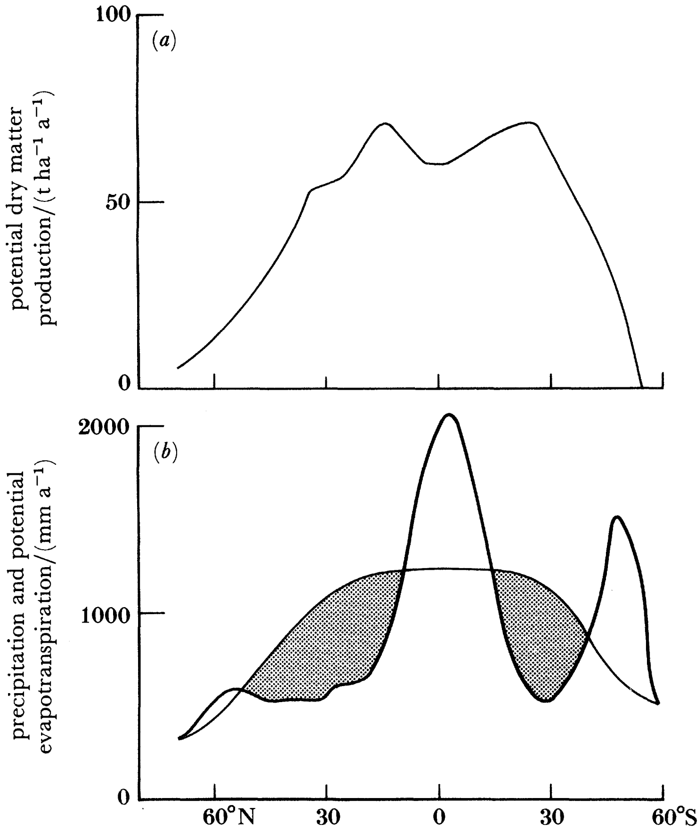

FIGURE 1. Latitudinal distribution of (*a*) potential dry matter production and (*b*) atmospheric water supply and demand over the land surfaces of the Earth. Estimates of potential dry matter production from calculations of potential photosynthesis (de Wit 1965), assuming half the assimilates respired (Amthor 1984). Estimates of annual precipitation are from Baumgartner & Reichel (1975) and of potential evapotranspiration from Budyko (1974). Shaded area represents deficit of precipitation below potential evapotranspiration.

to the often significantly negative effects of the large inter-annual and intra-seasonal climatic variations present in other agricultural regions. A reference to this important advantage can be found in the biblical comparison between Egypt's irrigated agriculture and the rain-dependent crops in Israel (Deuteronomy 11, vv. 10–17).

This comparison is still valid, as shown by an analysis of wheat yields in the two countries over the last 22 years. Statistical analysis of this data (figure 2) indicates that the irrigated wheat crop in Egypt yields an average of 50% more than the predominantly rain-fed crop in Israel, with less than half the year-to-year variation. After removing the time trend attributable to agrotechnological advances and represented by the fitted slope, the interannual variations in the irrigated wheat yield of Egypt have a standard deviation of 208 kg ha^{-1}, or 7 % of the mean, a figure similar to that found in England (Stanhill 1976). By comparison, the corresponding figure for Israel's rainfed wheat crop is 504 kg ha^{-1}, which is 26 % of the mean.

The potential negative aspects of arid land irrigation – salinization and impeded drainage – are unfortunately even more important than its positive features, and are attested to by numerous examples of once flourishing but long abandoned remnants of irrigated agriculture to be found in the Middle East, northwestern India and southwestern North America. It is

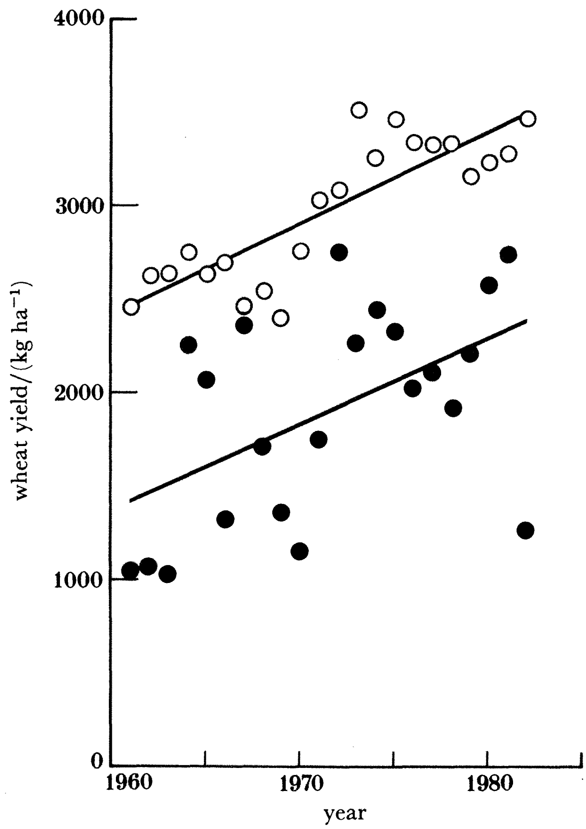

FIGURE 2. Size and stability of wheat yield in irrigated and non-irrigated arid zone agricultures. Lines represent linear regression of average national yield (Y in kilograms per hectare), on year of harvest (X); ○, Egypt: $Y = 49.4X - 94468$, $r^2 = 0.71$, $S(Y/X) = 209$, $F = 50$; ●, Israel: $Y = 45.0X - 86866$, $r^2 = 0.26$, $S(Y/X) = 504$, $F = 7$.

far more difficult to find an example of one that has not, and even in Egypt – the classic example of an arid land irrigation system that has remained productive over 5000 years – the linked problems of salinity and drainage, responsible for the destruction of most arid land irrigation schemes, have emerged during the last 200 years.

The following brief description of the development of irrigated agriculture in Egypt provides a case study of how these dangers arise.

IRRIGATION IN EGYPT

The simple, efficient and productive irrigation agriculture which developed in the Nile Valley during the early Dynastic Era some 5000 years ago was based on the cultivation of a single crop each year, predominantly winter cereals, but also including some flax and clover, on land irrigated by ponding the annual Nile flood in large basins. This saturated a sufficient depth of the deep fertile alluvial soil to provide crop water requirements up to harvest, at the same time leaching the soil of salts which had accumulated during the previous growing season. Silt, deposited by the annual flood at a rate averaging 9 cm per century, was both the origin of the soil and its source of fertility.

Extension of the cropping season beyond the post-flood winter–spring season appears to have

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begun in the Ptolemaic period (third century B.C.E). It required the construction and maintenance of a canal system from which water could be lifted to the flood-deposited, and therefore continuously rising, field level. By 1800, Napoleon's survey showed that one fifth of the total cultivated land was producing two crops a year under the so-called 'perennial irrigation' system. This area was rapidly expanded by Muhammed Ali to allow the large-scale cultivation of export crops, predominantly cotton. Barrages across the Nile were constructed to increase the water level in the canals during the summer irrigation season and so reduce the work needed to lift water to field level. By 1840 the water in the Delta canals could be maintained 4 m above the previous summer levels.

The effect of the rising water levels on crop yields was beneficial at first, allowing the simple human- and animal-powered water-lifting devices then available to provide sufficient water for the limited area under perennial irrigation. As this area expanded and the height of the water table continued to rise, damaging side-effects on crop yields emerged. These were caused by a reduction in the soil volume available for root exploitation, impaired leaching of salts from the rooting zone, and enhanced surface salination owing to increased evaporation from the soil surface wetted by capillary rise. Water loss by transpiration was also increased by the extension of the cropping season into the hot dry summer months, leaving salts carried in the transpired water in the upper soil layers. By 1947 Balls (1953) calculated that the rise in the water table had reduced the cotton crop yield to half of its potential.

With the completion ten years ago of the Aswan High Dam century storage scheme, complete inter- and intra-annual control of the Nile's flow within Egypt was assured and the last remnants of basin-irrigated land were converted to perennial cropping. Currently, each cultivated hectare of land in Egypt produces an average of five crops every three years, providing sufficient food energy for over eleven persons, compared with four persons in 1800.

An important negative result of the 'century storage' scheme, by which Nile water is stored behind the Aswan High Dam in Lake Nasser, is the increased salinity of irrigation water. This is largely because of the high evaporation loss from the shallow storage lake situated in one of the most arid regions of the globe. Since the construction of the scheme, the total dissolved salt content of Nile water at the head of the Delta has increased by 29%, from 0.184 to 0.238 kg m^{-3} (Khalil & Hanna 1984).

Approximately half of the 51×10^9 m^3 of water released annually for agriculture is lost to the atmosphere through transpiration and evaporation, leaving approximately six million tons of salt on the cultivated area. Nearly one-third of Egypt's cultivated area now suffers from salinity problems (Elgabaly 1977). Leaching of these salts is inhibited by poor drainage resulting from the high water table, largely attributable to the half of the irrigation water that is not lost to the atmosphere. This seeps to the groundwater in approximately equal volumes through the cultivated fields and from the 40 000 km long network of unlined irrigation canals which are full for all but two weeks of the year. Currently, two-thirds of the agricultural area suffers from drainage problems (Elgabaly 1977).

Deterioration in land fertility is not the only negative effect of the expansion of perennial cropping. It also led to the spread of a number of debilitating water-borne diseases among the rural population. In particular the year-round presence of open water needed for demand irrigation in arid lands encouraged the spread of schistosomiasis. Fortunately, the combined effects of public health measures and increased urbanization appear to have halted the spread of this disease (Miller *et al.* 1978).

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Before leaving this brief case study of the oldest and most successful arid land irrigation system, it should be emphasized that the threat to the long-term productivity of Egypt's irrigated agriculture, which has emerged during the almost two hundred year long process of Nile flood control and intensified cropping, should be balanced against the fourfold increase in carrying capacity that was achieved during the same period (table 1), largely as a result of these measures.

Table 1. Changes in human-carrying capacity of irrigated agriculture in Egypt between 1800 and 1972–1974

	1800	1972–1974
cultivated area 10^3 km^2	19.1	28.6
crop area 10^3 km^2	23.3	45.0
population (millions):		
total	2.5	35.8
rural as percentage of total	84	53
food production per unit irrigated area		
metabolic energy/(GJ ha^{-1} a^{-1})	17.2	47.5
edible protein/(kg ha^{-1} a^{-1})	140	330
human-carrying capacity (millions)	7.9	32.4

Data sources: Girard (1812); *Statistical yearbooks* (Central Agency for Public Mobilization and Statistics (Cairo)); F.A.O. *Production and trade yearbooks* (Rome).

Irrigation in Israel

Irrigated agriculture in Israel provides a striking contrast to that in Egypt, despite the similarities in climatic background and the on-demand availability of water in both systems. The major differences can be attributed to the very recent development of irrigated agriculture in Israel, which has allowed the combination of a centralized nationwide pressurized water-supply system with complete control of application by individual growers.

Thirty-seven years ago, less than 20% of Israel's cultivated area was irrigated, and this consisted largely of surface irrigation of citrus orchards in the central coastal plain. A multitude of shallow local wells were then used to supply water through ditches to basins around individual trees.

The total irrigated area has since risen sevenfold and is now nearly half the cultivated area. Of this, 80% is irrigated by sprinklers and the remaining 20% by drip systems. The expansion and intensification were achieved largely by the construction of the National Water Carrier, which was completed in 1964 and links the country's two major water sources: the Jordan head waters and the costal aquifer. Lake Kinneret (the Sea of Galilee), which is 200 m below sea level, serves as the system's major reservoir with a working capacity of 600×10^6 m^3, while the coastal aquifer has a safe storage volume of 2100×10^6 m^3. This total storage capacity of between 2500×10^6 and 3000×10^6 m^3 serves as a buffer for the very variable rainfall supplying the two water sources. In the last 30 years the standard deviation of the annual total volume of rainfall was 1170×10^6 m^3, 22% of the mean volume. The success of the National Water Carrier's operations is shown by the fact that the annual total water budget, which has averaged 1620×10^6 m^3 a year over the last decade, has not varied more than 5% from the mean despite the wide fluctuations in rainfall.

Changes in two key parameters of Israel's irrigated agriculture – water application and productivity – that have occurred during the last 34 years are illustrated in figure 3. The accelerating decline in the rate of water applied per unit irrigated area has been accompanied by a decrease in the relative importance of the cost of water as one of the inputs purchased by agriculture. At the same time, the relative importance of irrigation systems as part of the capital stock in agriculture has increased.

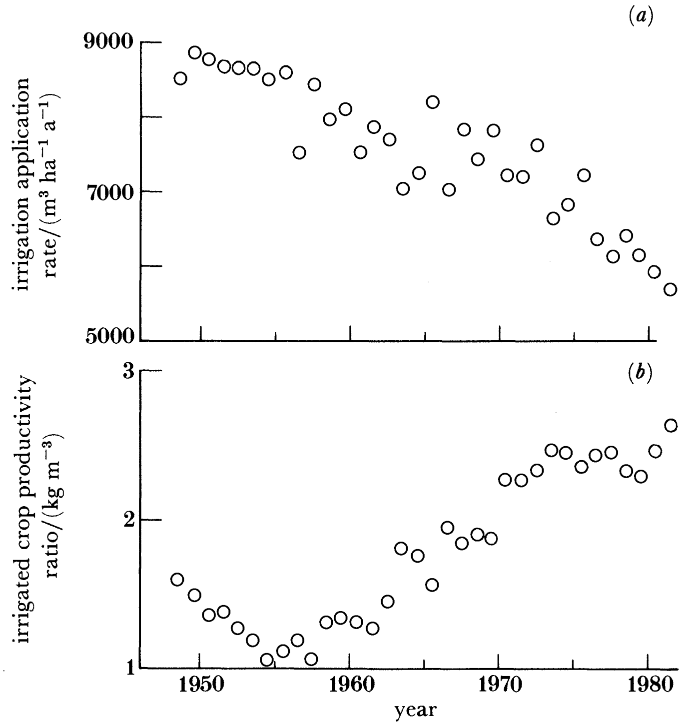

FIGURE 3. Changes in (*a*) water expenditure and (*b*) productivity of irrigated crop production for Israel 1948, 1949–1981, 1982. Average annual values for all of irrigated crop area are given (Central Bureau of Statistics 1984).

At the beginning of the 33-year period for which national statistics are avaiable, water application in Israeli agriculture averaged nearly 9000 m^3 a year for each hectare irrigated, half the national average applied in Egypt. The cost of water represented 12 % of the total inputs purchased by Israeli agriculture and the value of the irrigation systems constitued 6 % of the total capital stock in agriculture. Currently, water application averages 6000 m^3 ha^{-1} a^{-1}, comprising 6 % of the total input costs, while farm irrigation systems represent 20 % of the total capital stock in agriculture (Central Bureau of Statistics 1984).

The decrease in water application rates has been accompanied by an even more pronounced increase in the productivity of Israel's irrigated agriculture. This has been indexed in figure 3 in terms of the yield harvested from all irrigated crops per unit water applied. This ratio has increased from a minimum of 1 kg m^{-3} at the beginning of the period to a current value of $2\frac{1}{2}$ kg m^{-3}.

The reduction in water application rates and the increased productivity have been achieved by applying the results of a large-scale and ongoing research programme in crop water requirements. This was initiated about 30 years ago, at the same time as the National Water

Carrier. To date, approximately 250 field experiments have been done to determine the economically optimum irrigation régime for each major crop in each soil–climate region. Some 30 scientists are involved in irrigation-related research, mainly in the Ministry of Agriculture's Research Organization, with an additional 50 advisory officers and technicians employed by the Field Service in irrigation-related agricultural extension. The results of the research programme, summarized by Shalhevet *et al.* (1981), provided the basis for the legally enforced water allocation policy. This determines, on a monthly timescale, the amount of water each irrigator can use, including that which is pumped from privately owned wells.

At the individual farmer level, the cost of water plays a relative minor role in water conservation, owing to the significant government subsidy in the price of water. An example of this can be seen in the fact that the large regional differences in energy requirements for water distribution are not reflected in the cost of water. Thus, in Israel, as in most arid lands, water is used as an instrument in implementing national policy of regional development.

The centralized and legally enforced water policy has also allowed the development and allocation of new water sources of secondary quality. As 90% of the national water resources were in use upon the completion of the National Water Carriers, agriculture has been able to maintain its water allocation only by the substitution of brackish and sewage water for the increased water consumption by industry and domestic users. These two sources together now supply one-fifth of the total agricultural water consumption in Israel.

Factors determining irrigation demand in arid lands

The long- and short-term dangers of, and opportunities for, arid land irrigation, illustrated by the two examples given, can be related to the degree to which the timing and distribution of water application has been coupled to the irrigation demand.

Knowledge of irrigation demand is a necessary requirement for the maintenance of a permanently productive irrigated agriculture in arid lands and much has been learnt from research done during the last half-century. However, even with the available knowledge, the ability to apply it and the will to ensure equitable distribution between competing water users may be absent. These non-scientific aspects are particularly important in arid lands because of the economic, political and social importance of irrigation. Presumably, it is for this reason that centralized, command-irrigation control systems are prevalent in arid lands, in contrast to the autonomous, user-oriented demand systems that have commonly emerged in more humid regions (Kelly 1983).

To ensure a permanently productive agriculture in arid lands, irrigation must satisfy a number of demands: those of the atmosphere, crop, soil, hydrology, and economy. In considering these different demands, only those aspects particular to arid lands will be touched upon, as general features will be dealt with by other speakers at this symposium.

Atmospheric water demand

The size of this parameter, the forcing function for irrigation demand, makes its calculation and measurement simpler and more accurate than in humid areas, especially as high air temperatures increase the importance of the radiation balance, one of the climatic factors governing potential water demand which lends itself to accurate measurement and estimation. By contrast, where irrigation is on a small scale and extensive rather than intensive, and where widely spaced, tall row crops are grown, the advective aspects of atmospheric water demand become important and add considerably to the complexity of calculation.

The conservative nature of the atmospheric water demand in arid climates is of considerable practical importance, as continuous and widespread measurements of the parameter may not be needed for long-term planning or even for a simple irrigation control system. The contrast between inter-annual variaton in arid and humid climates is shown by the following comparison of the coefficients of variation calculated from two 22-year long series of open water surface evaporation measurements at typical humid and arid sites. At Wellesbourne, in the western Midlands of England (52° 12′ N, 1° 35′ W, 60 mM.S.L), the mean daily evaporation during July (the month of maximum evaporation) averaged 3.1 mm and the coefficient of inter-annual variation was 21%. At Gilat, in the northern Negev of Israel (31° 20′ N, 34° 40′ E, 150 m mean sea level), the corresponding figures were 9.1 mm and 6.5%. Thus, although the mean maximum atmospheric water demand was three times greater at the arid zone station, the inter-annual variation was only one third of that in the temperate climate.

The contrast in variability of atmospheric water demand becomes even more marked when the effect of rainfall variation is taken into account. Thus, at Gilat, no rain fell during the month of maximum evaporation and so the variation in water deficit (evaporation minus rainfall) was identical to that in evaporation. At Wellesbourne, the temperate zone station, the inter-annual variation in water deficit was 71%, more than three times that of evaporation.

Crop water demand

Water demand from irrigated crops growing under arid conditions is often less than the atmospherically determined potential demand, because the latter exceeds the maximum water-uptake and transport rates possible through the soil–plant continuum. A comparison of crop coefficients relating crop evapotranspiration to the atmospheric demand shows reductions of between 5 and 10% for crops growing under low atmospheric humidity compared with the same crops under humid conditions (Doorenbos & Pruitt 1984).

Under the stable climatic conditions characteristic of arid lands, modern high-frequency irrigation systems enable crop evapotranspiration to be maintained at levels close to the atmospheric demand with water application efficiencies approaching 90%. The resulting high yields and reduced water losses have made it increasingly possible and profitable to use irrigation systems to apply crop nutrients, pesticides and herbicides as well as to modify the crop microclimate.

The major advantage of incorporating agrochemicals in irrigation water is the reduced cost of application, although in a number of cases an increase in efficiency has also been demonstrated.

Some, although not all, recent studies have shown this to be the case with applications of nitrogen, particularly in sandy soils (Dasberg *et al.* 1983; Feigin *et al.* 1982; Rehm & Wiese 1975). Carefully modulated concentrations of nitrogen in the irrigation water can maintain a near-optimum content in the soil around the root system, reducing voltilization and leaching losses and thus environmental pollution as well as waste. Volatization losses of ammonia from urea, the major low-cost N source suitable for application through the irrigation system, can be further reduced by the use of additives to slow hydrolysis, in particular, chlorides of K, Ca and Mg (Rappaport & Axzley 1984).

In a wide-ranging study Chalfant & Young (1982) demonstrated that the application of a large number of insecticides to many pests and crops by using overhead sprinkler systems was as effective as aerial or ground sprays, and could be achieved at a much reduced cost and energy consumption. In the case of a number of nematicides, application through drip irrigation systems has been shown to be more efficient than conventional methods (Overman 1976), and recently the application of herbicides by the same method has also been shown to be effective (Dowler *et al.* 1982).

The last reference shows that the characteristcs of the irrigation system can affect the efficiency of the chemical applied, and this aspect of 'chemigation' must be considered together with that of the possible physical and chemical interactions, both long and short term, between nutrients and pesticides when they are jointly applied in irrigation (Saltzmann *et al.* 1984).

In arid zones the most important microclimate modification for which irrigation is used is to cool the crop canopy when damagingly high temperatures occur. Automated overhead sprinkler systems have been used successfully for this purpose with fruit crops introduced from more temperate climates (Unrath 1972) as well as for cooling glass and animal housing. In some frost-liable desert sites used for winter production of vegetables, similar systems have been used to protect crops from damagingly low temperatures.

In both cases, the modification of the microclimate is a result of the high latent heat of water. Another physical property of water used for climate modification is its high specific heat, used in some marginal climate areas to protect young rice crops with water warmed in shallow, solar-heated ponds. The high radiation-absorption properties of water when in the fine droplet state have also been used experimentally in arid zones using high-pressure, frog-irrigation systems to reduce excessive solar heating by day, and long-wave radiation cooling by night.

Soil water demand

Irrigation in arid lands has traditionally been used to maintain productivity by modifying the physical and chemical properties of the soil, as well as to satisfy crop water demands. Although irrigation is no longer widely used as a means of land preparation and cultivation in arid zones, its role in ameliorating the soil's chemical composition is of major and increasing importance. This is a result of the growing use of brackish, industrial and domestic waste-water sources which are rich in salts. In addition the increasing use of fertilizers, pesticides and herbicides adds a further salt burden to irrigated land.

The classical method of leaching the soil of salts accumulated during the irrigation season was to inundate the fields before cropping, as in Egypt. The rule-of-thumb recommendation concerning the depth of water required for this purpose was that it should equal the depth of soil from which 80% of the total soluble salt content was to be leached.

In the last two decades, lysimeter studies and mathematical modelling have established that leaching can be achieved more efficiently by intermittent applications of water, and it is now standard practice in many arid areas subject to salinity problems, to add to the crop water requirement an amount sufficient to maintain the average salt concentration in the major root zone at a level below the yield-limiting threshold.

The fraction added, known as the leaching requirement, depends primarily on the crop's sensitivity to salinity, the salt concentration in the irrigation water and in the soil, and, to a lesser extent, on the nature of the salts and soil and climate characteristics (Bresler *et al.* 1982). The leaching requirements of the four major crop types are presented in table 2 together with the salinity thresholds for water and soil at three levels of yield decrement. It can be seen that there is considerable variation both between and within the crop types.

Table 2. Leaching requirements and threshold salt concentrations in irrigation water and soil solution needed to avoid crop yield decrements

crop type	yield decrement (percentage)	fruit	vegetable	forage	field
number of crops averaged		11	14	19	14
leaching requirement[a]					
as fraction additional to crop water requirement	0	0.07 ± 0.02	0.05 ± 0.02	0.07 ± 0.03	0.08 ± 0.04
	10	0.10 ± 0.02	0.08 ± 0.02	0.10 ± 0.03	0.11 ± 0.04
	25	0.14 ± 0.01	0.13 ± 0.01	0.13 ± 0.04	0.14 ± 0.03
soil salinity					
electrical conductivity of saturation extract/(dSm^{-1} at 25 °C) in root zone from which two thirds of water was extracted	0	1.7 ± 0.8	1.9 ± 0.8	3.8 ± 2.1	3.1 ± 2.4
	10	2.5 ± 1.5	2.7 ± 1.1	4.3 ± 2.3	4.7 ± 3.0
	25	3.7 ± 2.5	4.1 ± 1.2	7.5 ± 2.8	6.5 ± 3.7
irrigation water salinity					
electrical conductivity of irrigation water/(dSm^{-1})	0	1.2 ± 0.5	1.2 ± 0.6	2.5 ± 1.4	2.4 ± 1.7
	10	1.7 ± 1.0	1.9 ± 0.6	3.5 ± 1.5	3.1 ± 2.0
	25	2.4 ± 1.7	2.8 ± 0.8	5.0 ± 1.9	3.7 ± 2.3

Results given as average values and intercrop standard deviation.
Data sources: Mass & Hoffmann (1977); Shainberg & Oster (1978).
[a] Corresponding to soil and water threshold salinities given.

Hydrological water demand

Irrigation often constitutes a major element in the water balance of arid lands, and in certain circumstances hydrological requirements may modify irrigation management. An example is provided by the need to reduce the total salt load draining from irrigated areas. This requirement was an important motive in the development of the previously outlined 'minimum leaching concept', as it has been shown that the amount of salt released from unsaturated mineral formations is dependent on the amount of water leaching through them.

Other hydrological roles for irrigation are in underground water storage to avoid high evaporation losses, and also when disposing of, or reclaiming, polluted water. The water source in such schemes may be surface runoff during the rainy season or when irrigation water requirements are low, and waste waters of domestic, industrial or even agricultural origins, i.e. the tail waters draining from irrigated land. The major hydrological role of the irrigated crop surface in such cases is to maintain a high water infiltration rate to the aquifer, and forage crops are particularly suitable for this purpose. In addition, many are resistant to salinity (table 2), remove significant amounts of salt by uptake, and do not pose a health hazard with contaminated water.

Economic water demand

Significantly more water is transpired per unit crop yield in arid than in temperate climates (Stanhill 1985). This physiological disadvantage, together with the high cost and even higher shadow price for water in arid lands, often makes it difficult to justify irrigated agriculture for basic food production on purely economic grounds despite the high yields that can be achieved (Carruthers & Clark 1981).

Two examples of irrigated wheat production under arid conditions illustrate this point. In the Negev area of southern Israel, where some wheat is grown with supplementary irrigation in dry winters, the average marginal yield response reported was 1.1 kg m^{-3} (Shalhevet *et al.* 1981), considerably below the response needed to pay the full cost of the water. In Saudi Arabia wheat has recently been very successfully produced by using modern demand-irrigation systems; despite the high yields, the cost of production is reported to be five times the world market price (Gowers 1984).

Thus, although modern irrigation methods allow considerable savings to be made in water requirements in comparison with traditional gravity-flow command systems, their high capital and operating costs, in terms of energy as well as of money, mean that the water saved is too expensive for basic food production.

Recent developments in arid land irrigation

Many of the recent developments discussed, together with others such as computer design and operation of irrigation and remote sensing for monitoring crop water stress, have been used with pressurized systems, adding to their already high capital and operating costs. It is only in the last decade that attention had been paid to increasing the efficiency of the gravity-flow irrigation systems with their intrinsically lower capital costs and energy requirements.

The three major modes of increasing the efficiency of surface irrigation are the addition of runoff recovery systems, i.e. the collection and reuse of tail waters, relevelling borders and basins to reduce gradients, and modulating water-inflow rates to increase the rate of infiltration and its uniformity.

Recently, computer programs have been developed for designing complex gravity-flow irrigation systems which include runoff recovery. These often reduce the cost and time required for construction as well as design. Relevelling irrigation borders and basins can now be done with great precision by using laser equipment (Dedrick *et al.* 1982). Perhaps the most promising progress has been in developing techniques of modulating water-inflow rates to furrows which are suitable for relatively simple and cheap automatic control.

One such system (the 'surge-flow' system), cycles water inflow to furrows through a pneumatically operated pipe conveyance and distribution system. Water application efficiencies demonstrated in the field are equal to those of sprinkler and drip irrigation and show a much reduced spatial and temporal variability compared with standard gravity methods (Keller 1981). In another system, 'cable irrigation', a single pipe at the head of the furrow-irrigated field contains a plug whose position is controlled by a cable and which forces water out through orifices drilled opposite the furrows. Field tests have shown application efficiencies above 70% (Goel *et al.* 1982) and the area under this system in the arid western states of the U.S.A. is reported to be almost 1000 ha, having doubled each year since its introduction in 1981.

An example of the use of new irrigation scheduling techniques for surface application systems under arid conditions is provided by the very recently introduced Californian Irrigation Management Information System (C.I.M.S). This consists of 40 automatic weather stations distributed throughout the state's irrigation districts. Each station is interrogated daily from the central computer facility, where the previous day's evapotranspiration and crop water requirement are estimated by using the approach developed by the F.A.O. (Doorenbos & Pruitt 1984). Modern techniques of high-speed data transmission distribute the estimates to the irrigation districts controlling water-distribution schedules, as well as to irrigation consultants and individual growers.

Remote sensing is a particularly suitable technique for use in irrigation management in arid lands because of the cloudless skies, lack of haze and great contrast between irrigated and surrounding surfaces. The information can be used to detect crop stress – indicating the need for irrigation – and also to monitor irrigation performance as indicated by crop uniformity. Such information can be obtained at 16-day intervals from the current Landsat satellite with a spatial resolution of 30 m (figure 4, plate 1).

If integrated, these recent developments could provide an efficient, automatic, yet economic system of demand irrigation that could transform arid land agriculture.

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FIGURE 4. Remotely sensed image of an irrigated area in the arid NW Negev of Israel, showing discrete separation within a single-centre pivot system (31.1.83, 31° 20′ N, 34° 29′ E). The image, taken from Landsat 4, consists of a three-times enlargement of a thematic mapper classification, using the 0.52–0.60, 0.63–0.69, 0.76–0.90, 1.55–1.75 and 2.08–2.35 μm wavebands. (Courtesy of D. W. Mooneyhan, N.A.S.A. Earth Resources Laboratory, Mississippi, U.S.A.)

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Discussion

E. B. Worthington (Colin Godman's, Furners Green, Sussex). So far we have heard much about the quantity but little about the quality of irrigation water. An international conference on irrigation in arid lands in 1976 heard much about the Russian studies on the great rivers flowing into the Caspian Sea and Aral Sea: the drainage from irrigation schemes is returned to the river and is reused successively four or five times downstream with increasing salinity, with specially adapted crops. Has Israel similar experience?

For Egypt, where the River Nile no longer functions as a drain to the sea and all salts in solution finish up in the soil, it would seem that a limit is set to the future. Has it been estimated how the process could be adjusted to create a self-perpetuating system, for example by the much increased drainage of irrigated land?

G. Stanhill. The amount of water draining through irrigated land in Israel is relatively small, and in the central coastal plain amounts to approximately 15% of the amount applied. This drains to the coastal aquifer, helping to leach salts from the topsoil and adding to the aquifer storage which is used to buffer the large inter- and intra-annual variation in water supply.

The important role that drainage has to play in regulating the salt balance of Egypt's irrigated land is well recognized, and the major drainage projects, under construction are planned to restore and maintain the land's fertility by increasing the efficiency of the system and the reuse of drainage waters.

D. E. Angus (Department of Civil and Agricultural Engineering, University of Melbourne, Australia. I was interested in Dr Stanhill's comment that as well as a progressive reduction in the cost of irrigation water in Israel over the past few decades, there has also been a significant reduction in water use per hectare. The claim is sometimes made that growers in the irrigation areas of southeastern Australia lack incentive not to use more water than they really need, because of relatively low cost of water there, and that therefore the price of water should be increased. At present some of the water finds its way to the relatively shallow water table, thus exacerbating the salinity problem. Whilst most growers might be considered to be efficient irrigators, the unnecessary use of too much water by a small minority affects not only their own farms, but also the surrounding area. How does Israel cope with this sort of problem?

G. Stanhill. Over-irrigation in Israel is prevented by the efficient application of the National Water Law. This allocates water to individual farms on a monthly basis according to the crops grown and the soil and climatic region as determined by field reseach. As the allocation is based on an irrigation efficiency of 80%, over-irrigation does not occur on any scale and does not contribute to the salinity problem.

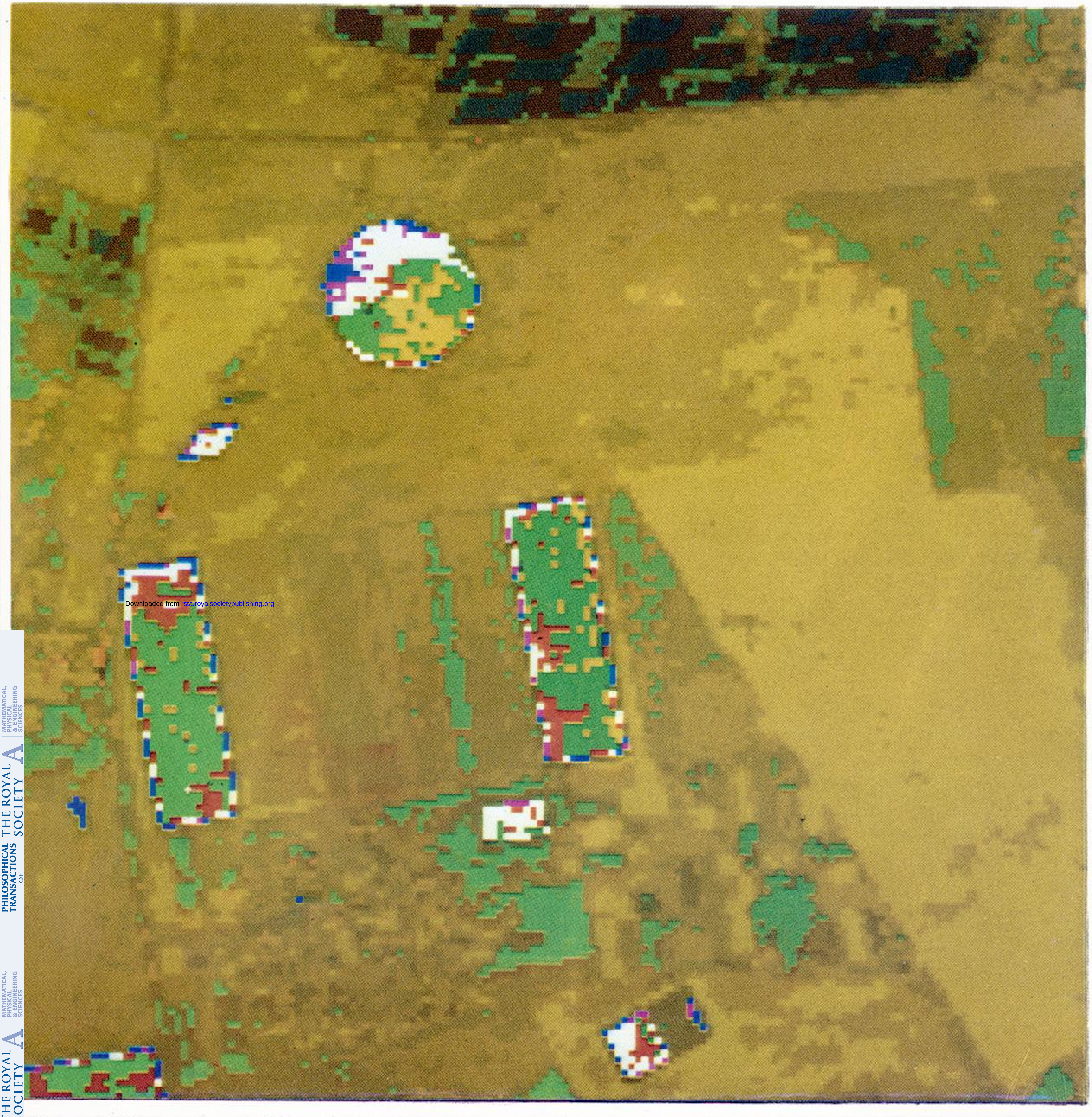

FIGURE 4. Remotely sensed image of an irrigated area in the arid NW Negev of Israel, showing discrete separation within a single-centre pivot system (31.1.83, 31° 20′ N, 34° 29′ E). The image, taken from Landsat 4, consists of a three-times enlargement of a thematic mapper classification, using the 0.52–0.60, 0.63–0.69, 0.76–0.90, 1.55–1.75 and 2.08–2.35 μm wavebands. (Courtesy of D. W. Mooneyhan, N.A.S.A. Earth Resources Laboratory, Mississippi, U.S.A.)

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