Small-scale irrigation for arid zones

Principles and options

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Preface

This publication is an attempt to distil current information on irrigation methods that might be appropriate, and to offer some ideas on the possible adoption and adaptation of such methods by small-scale farmers in the semi-arid areas of sub-Saharan Africa. At issue is a vast region greatly in need of enhanced and more stable agricultural production. Yet the irrigated sector here has, to date, suffered from underdevelopment. Numerous efforts to develop the sector have foundered in the past, possibly because the approach has been inappropriate to the physical and socio-economic conditions prevailing in the region.

There can be no single panacea to the problem of ensuring food security in Africa, nor to the task of developing irrigation there. The continent is too varied for any single approach to apply in all cases. A multiplicity of possibilities exists, and the most appropriate ones depend in each case on local agronomic, economic and social conditions. In some cases, large-scale systems, centrally controlled (by commercial or government enterprises) may be the quickest way to increase production. Concurrently, however, the development of irrigation should take place on small-scale farms operated by individual farmers or by associations of farmers. It is to promote the latter form of development that this publication is primarily directed.

A positive and realistic approach, in awareness of the real problems but undeterred by them, is called for. The aim of this publication is to present practical options that are consistent with such a new approach. An effort is made to do so in simplified but not simplistic terms, in a manner that may be useful to a wide spectrum of potential readers, from policy-makers to extension workers in the field, and that is consistent with FAO's Special Programme for Food Security in Africa.

As the reader will quickly notice, this presentation is not a purely technical how to handbook. It is, rather, a what and why elucidation of the conceptual foundations of modern irrigation that should underlie decision-making in the area of irrigation development. Whereas ready-made prescriptions tend to be specific and inflexible, and hence rarely apply as new problems arise in changing circumstances, a basic understanding of principles should enable practitioners to adjust their thinking and actions to unforeseen situations. The ultimate purpose is therefore to foster an informed awareness of both the potentialities and the limitations of modern irrigation methods, and thus to guide the selection and adaptation of appropriate technologies for greater sustainable production and better resource utilization.

In taking this approach I have avoided dealing with traditional surface irrigation methods (including border, basin and furrow methods) that have been described repeatedly in the past and are generally well known in the region. Such methods have long served for the irrigation of crops such as rice, sugar cane and cotton. Rather, attention is concentrated on the development of irrigation for such food crops as fruit, grain, legume and vegetable crops (including root crops) that can be grown in water-scarce semi-arid or arid areas. It is in such areas of sub-Saharan Africa that small-scale, low-volume, low-cost, partial-area, high-frequency irrigation methods appear to offer considerable possibilities that are yet to be realized.

Daniel Hillel

Acknowledgements

As author of this report, I wish to express my gratitude, first of all, to Dr Jacques Diouf, Director-General of the Food and Agriculture Organization of the United Nations, whose personal interest and determination to make the work of FAO more relevant to the field have inspired this project. I also acknowledge the valuable advice and encouragement of Messrs Wim Sombroek, formerly Director of the Land and Water Development Division, Robert Brinkman, present Director, and Hans Wolter, Chief of the Water Resources Development and Management Service within that Division. Other members of the Division - especially Messrs Lucien Vermeiren, Arum Kandiah and Bo Appelgren - offered information and advice as well. The drawings were made with the able and willing assistance of Mr Han Kamphuis, who deserves special thanks. So does Dr Cynthia Rosenzweig, who gave much of her time to help in shaping this publication.

Finally, I acknowledge with deep appreciation the support granted me by the Rockefeller Foundation of New York.
1 Chapter 1: Food security and irrigation

The outlook for the food security of many developing nations is a cause for serious concern. Widespread denudation and accelerated erosion diminish the productivity of both cultivated and grazed rain-fed lands. Especially vulnerable are semi-arid regions to climatic instability and frequent droughts. At the same time, depletion and pollution of limited freshwater resources and competing demands for water - among neighbouring states as well as between different sectors within each state - constrain the further expansion of irrigation.

The problem of food security is exacerbated by the rapid growth of population and hence of the demand for food. In fact, the prices of foodstuffs in the world market have recently begun to rise. Beyond that looms the spectre of a fundamental change in climate (a consequence of the enhanced greenhouse effect), that may increase the severity and variability of weather and thus disrupt established systems of production. Such a change could require expensive investments in modifying existing systems and establishing new ones.

All these problems are particularly acute in the continent of Africa, parts of which are already in the throes of a severe population-environment crisis. The population of sub-Saharan Africa, now nearing 600 million, is projected to double by the year 2020. Therefore, a much greater effort must be made by the international community to assist the African nations in the difficult task of improving their prospects for food security (Figure 1).

**FIGURE 1**

*Water availability in Africa*

*Source: Irrigation and water resources potential for Africa, FAO (1987).*

Clearly, irrigation can and should play an important role in raising and stabilizing food production, especially in the less-developed parts of Africa south of the Sahara. There are, however, many obstacles to the rapid development of irrigation there. Large parts of the region have only limited freshwater resources. In other areas, potential resources are insufficiently known to permit reliable planning. Even where water resources are definitely known to be substantial, other conditions may not
be conducive to irrigation development. Such conditions may include unfavourable topography and soils, distant markets and inadequate infrastructure, as well as lack of credit, labour, information and other services to farmers. These problems, while real, do not entirely explain the historical failure to develop the full irrigation potential of sub-Saharan Africa. The data available (Table 1) on that potential suggest that it is considerable. By some estimates it may be as great as 30 million hectares, whereas other estimates project less than 10 million hectares. A reasonable figure may be in the order of 15 to 20 million hectares which, if fully developed and properly managed, could contribute significantly to the food security of the African continent. The fact that some earlier efforts at irrigation development produced disappointing results may be more the consequence of flaws in approach and implementation than of truly insurmountable obstacles. The time is ripe for a new approach.

Irrigation is the supply of water to agricultural crops by artificial means, designed to permit farming in arid regions and to offset drought in semi-arid regions. Even in areas where total seasonal rainfall is adequate on average, it may be poorly distributed during the year and variable from year to year. Where traditional rain-fed farming is a high-risk enterprise, irrigation can help to ensure stable production.

1.1 TABLE 1

**Sub-Saharan Africa: estimates of irrigated areas in relation to potential, 1991**

<table>
<thead>
<tr>
<th>Country</th>
<th>Irrigation potential (ha)</th>
<th>Area under irrigation (ha)</th>
<th>Total in % of potential</th>
</tr>
</thead>
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<tr>
<td>Angola</td>
<td>3 700 000</td>
<td>75 000</td>
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<td>Benin</td>
<td>300 000</td>
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<td>Area (sq km)</td>
<td>Population Density</td>
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<td>Mozambique</td>
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<td>106 710</td>
<td>3.5</td>
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<td>Namibia</td>
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<td>9 700</td>
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<td>Seychelles</td>
<td>1 000</td>
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<td>Sierra Leone</td>
<td>807 000</td>
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<td><strong>Sub-Saharan Africa</strong></td>
<td><strong>39 366 490</strong></td>
<td><strong>6 181 422</strong></td>
<td><strong>15.7</strong></td>
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</tbody>
</table>

*Source: Irrigation in Africa - a basin approach, FAO (in press).*

Irrigation has long played a key role in feeding expanding populations and is undoubtedly destined to play a still greater role in the future. It not only raises the yields of specific crops, but also prolongs the effective crop-growing period in areas with dry seasons, thus permitting multiple cropping (two or three, and sometimes four, crops per year) where only a single crop could be grown otherwise. With the security provided by irrigation, additional inputs needed to intensify production further (pest control, fertilizers, improved varieties and better tillage) become economically feasible. Irrigation reduces the risk of these expensive inputs being wasted by crop failure resulting from lack of water.

The practice of irrigation consists of applying water to the part of the soil profile that serves as the root zone, for the immediate and subsequent use of the crop. Well-managed irrigation systems are those which control the spatial and temporal supply of water so as to promote growth and yield, and to enhance the economic efficiency of crop production. Such systems apply water in amounts and at frequencies calibrated to answer the time-variable crop needs. The aim is not merely to optimize growing conditions in a specific plot or season, but also to protect the field environment as a whole against degradation in the long term. Only thus can water and land resources be utilized efficiently and sustainably. On the other hand, poorly managed irrigation systems are those which waste water and energy, deplete or pollute water resources, fail to produce good crops and/or pose the danger of soil degradation.

The vital task of increasing and stabilizing food production in drought-prone regions must therefore include a concerted effort to improve on-farm water management. Some traditional irrigation schemes need to be modernized so as to achieve higher yields as well as better resource utilization. New schemes being planned should likewise be based on sound principles and techniques for efficient water use and for optimizing irrigation in relation to all other essential agricultural inputs and operations.

In recent decades, revolutionary developments have taken place in the science and art of irrigation. A more comprehensive understanding has evolved regarding the soil-crop-water regime as affected by climatic, physiological and soil factors. These conceptual developments have led to technical innovations in water control that have made possible the maintenance of near-optimal moisture and nutrient conditions throughout the growing season.

Foremost among these innovations are techniques for high-frequency, low-volume, partial-area
applications of water and of nutrients at rates calibrated to satisfy crop needs. Such methods are now applied on a large scale in industrialized countries, where they tend to be highly mechanized and to rely on energy-intensive labour-saving technologies. However, they need not necessarily depend on expensive manufactured equipment and intensive energy inputs. Instead, they can be simplified to fit the special low-capital circumstances of the less-developed countries. Moreover, they are flexible enough to permit downscaling in order to fit the requirements of small-scale farmers.

Properly applied, the new irrigation methods can raise yields while minimizing waste (by runoff, evaporation and excessive seepage), reducing drainage requirements and promoting the integration of irrigation with essential concurrent operations (fertilization, tillage and pest control). The use of brackish water has become more feasible, as has application to sandy, stony or steep lands previously considered unirrigable. Other potential benefits include increased crop diversification and cropping intensity.

Despite all the new advances and promising possibilities, wasteful practices still persist in many irrigated areas. In some places, inefficiency is perpetuated by fixed, institutionally imposed standards that foster unmeasured and typically excessive applications of water. Such inflexible regimes offer farmers no incentive to improve water management and even discourage them from taking independent initiatives to do so. However, institutional inertia and rigid patterns are only part of the problem. Some of the new irrigation systems developed in the industrialized countries are in fact too complex, energy-intensive, dependent on expensive imported equipment and large in scale to be directly applicable to the low-capital, low-technology circumstances of the less-industrialized countries, where farming is often practised on a small scale and the relative costs of labour and capital are very different.

Hence, ready-made modern technology often fails when introduced arbitrarily into developing countries. Elaborate and expensive systems (such as large centre-pivot booms and even drip-irrigation assemblies complete with automated pumps, filters, pressure regulators, metering valves and fertilizer injectors), imported and installed in the grand hope of achieving instant modernization, typically fail for lack of expert maintenance and spare parts. Such installations can quickly become white elephants - idle monuments to hasty "progress" relying on ill-adapted technology. Instead of introducing prepackaged hardware systems, developers should apply the best principles of efficient irrigation, in so far as possible using indigenous skills and materials. Rather than simply transfer Western technology as such, the aim should be to adapt or redesign technology flexibly so as to suit the prevailing conditions and requirements.
Why is it that irrigated farming in some areas fails to achieve its potential benefits? The problem is not inherent in the principle of irrigation as such, but in the frequently inappropriate practice of it. More often than not the fault lies in the unmeasured and generally excessive application of water to land, with little regard either for the real cost of extracting the water from its source and delivering it to the farm, or for the cost of restoring the water resource after it has been depleted or polluted. By deliberately maintaining a low price for water, governments perpetuate the false notion that fresh water is a free good, rather than the scarce and expensive resource that it really is. It is the universal fallacy of humans to assume that if a little of something is good, then more must be better. In irrigation (as indeed in many other activities), just enough is best, and by that is meant a controlled quantity of water that is sufficient to meet the requirements of the crop and to prevent accumulation of salts in the soil, no less and certainly no more. The application of too little water is an obvious waste, as it fails to produce the desired benefit. Excessive flooding of the land is, however, likely to be still more harmful, as it tends to saturate the soil for too long, inhibit aeration, leach nutrients, induce greater evaporation and salin-ization, and ultimately raise the water-table to a level that suppresses normal root and microbial activity and that can only be drained and leached at great expense. Apart from wasting water, therefore, excessive irrigation contributes to its own demise by the twin scourges of water-logging and soil salinization. Instead of achieving its full potential to increase and stabilize food production, irrigation in such cases is in danger of becoming unsustain-able. The ultimate economic and environmental consequence of poorly managed irrigation is the destruction of an area's productive base. The cost of rehabilitating the land after it has been degraded may be entirely prohibitive. From the point of view of water use, some large-scale irrigation projects operate in an inherently inefficient way. Where water is delivered to farmers on a fixed schedule and charges are set per delivery regardless of the actual amount used, irrigators tend to take as much water as they can while they can. This typically results in overirrigation, which not only wastes water but also contributes to project-wide problems associated with the disposal of return flow and elevation of the water-table. Especially difficult to change are management practices that lead to waste, not necessarily because of insurmountable technical problems or lack of knowledge, but simply because it appears more convenient or economical in the short term to waste water rather than to conserve it. Such situations occur when the price of irrigation water is lower than the cost of the labour or of the equipment needed to avoid overirrigation. The classical method of irrigation, which evolved in the major river valleys of the Near East, South Asia and East Asia, consists of flooding the land to some depth with a large volume of water so as to saturate the soil completely, then waiting some days or weeks until the moisture thus stored in the soil is nearly depleted before flooding the land once again. In this low-frequency, high-volume, total-area pattern of irrigation, the typical cycles consist of repeated periods of excess soil moisture alternating with periods of likely insufficiency. Optimal conditions occur only briefly in transition from one extreme condition to the other (Figure 3).
moisture). Moreover, applying the water at spatially discrete locations rather than over the entire area has the effect of keeping much of the soil surface dry, thus helping not only to reduce evaporation but also to suppress proliferation of weeds (Figures 4, 5, 6 and 7).

**FIGURE 4**
The pattern of wetting under furrow irrigation: if furrows are closely spaced the entire root zone is wetted to near-saturation

**FIGURE 5**
The pattern of wetting under sprinkler irrigation: to compensate for the uneven distribution of water around each sprinkler, adjacent sprinklers are spaced closely enough to overlap (thus tending to equalize the spatial distribution of water)

**FIGURE 6**
A portable hand-move sprinkler irrigation system
This optimization of soil moisture is difficult to achieve with the traditional flood irrigation methods still dominant in many river valleys. As a result, the new approach to irrigation management has not yet been adopted very widely in developing countries. Although it is gaining ground gradually, its progress should be encouraged and accelerated wherever appropriate.

Ideally, the new irrigation systems should convey water to the field in concrete-lined channels so as to avoid seepage losses, or preferably in closed conduits that avoid pollution and allow pressurizing of the water thus delivered. In the field, the water can be distributed via low-cost, weathering-resistant plastic tubes, and be applied to the root zone by means of drip emitters, microsprayers or porous bodies placed at or below the soil surface. Human labour and local materials may substitute for industrially produced devices where such are unavailable or too expensive, while retaining the principles of efficient irrigation.

As the frequency of irrigation increases, the infiltration period becomes a more important part of the irrigation cycle. With small daily (rather than massive weekly or monthly) applications of water, the pulses of added water are damped down within a few centimetres or decimetres of the surface, so the flow below that depth is essentially steady. A skilled irrigator can control the moisture content of the root zone as well as the rate of internal drainage by adjusting the rate and quantity of application according to the soil's infiltrability, the soil solution's concentration, and the climate-imposed evaporative demand. Thus the irrigator can manage the system optimally so as to both increase yields and conserve water (Figures 6 and 7).

The long-accepted notion that the entire volume of the root zone must be wetted to capacity at each irrigation has been contradicted by recent experience proving that a crop can fare well when the wetted zone is restricted to a fraction of the soil volume - 50 percent, or even less. This is of course, that the supply of moisture and nutrients in that partial volume is sufficient to satisfy full crop needs.

Since a high-frequency irrigation system can be adjusted to supply water at very nearly the exact rate required by the crop, the irrigator no longer needs to depend on the soil's ability to store water during long intervals between irrigations. Hence water storage properties, once considered essential, are no longer decisive in determining whether a soil is irrigable. New lands, until recently believed to be unsuited for irrigation, can now be brought into production. Examples are coarse sands and gravels, where moisture storage capacity is very low and where the conveyance and spreading of water by surface flooding would cause too much seepage. Such soils can now be irrigated even on sloping ground by means of drip, trickle, microsprayer or soil-embedded porous emitters that apply the water frequently or continuously to the root zone at a controlled rate.

Though they offer many advantages, high-frequency partial-volume systems have shortcomings too.
With only a fraction of the potential root zone wetted, there is less moisture storage in the soil, so the crop depends vitally on the continuous operation of the system. Any short-term interruption of the irrigation (whether caused by neglect, mechanical failure or water shortage) can quickly result in severe distress to the crop. The imperative to maintain continuous operation is difficult to meet if the system depends on costly and vulnerable equipment imported from abroad. The system must therefore be simplified so as to make the local farmers self-reliant. In general, it is difficult to change a pre-existing pattern of human behaviour and institutional norms. An infrastructure designed for one mode of operation cannot readily be converted to another. Habits and traditions, once established, acquire an inertia, with vested interests in maintaining the status quo and a resistance to reforming it. That is why it is considered so important to start new irrigation projects appropriately by instituting efficient practices from the outset.

3 Chapter 3: Improving water-use efficiency

In general, the term efficiency is used to quantify the relative output obtainable from a given input. Referring to the use of water in irrigation, efficiency may be defined in various ways, depending on the nature of the inputs and outputs to be considered. An economic criterion of efficiency, for example, might be the financial return obtained from irrigation in relation to the investment made in the water supply. The problem here is that costs and prices fluctuate from year to year and vary widely from place to place. Another problem is that some of the costs of irrigation and some of the benefits cannot easily be quantified in tangible economic or financial terms, especially where a market economy is not yet fully developed. Often, only the short-term costs and immediate benefits are seen, whereas the long-term advantages or disadvantages are not fully realized at the outset. How is it possible to assess the economic value, for instance, of saving the population of a region from the potential effects of a drought, if the probability or severity of future drought events is not known? To some degree, therefore, it is necessary to operate in a state of uncertainty.

In more restricted technical terms, what irrigation engineers often call conveyance efficiency is defined as the net amount of water delivered to a farm, as a fraction of the amount taken from some source. The difference between the two amounts represents the seepage and evaporative losses incurred en route from source to field. Not generally considered in the term conveyance efficiency is the possible loss of water quality through pollution - such as that caused by wading animals or by human use of the canal water for washing and waste disposal.

The term on-farm application efficiency or field application efficiency generally refers to the fraction of the water volume applied to a farm or a field that is "consumed" by a crop, relative to the amount applied. Crop consumption consists of the amount of water actually absorbed by the crop, most of which is generally transpired to the atmosphere (only a small fraction, often less than 1 percent, being retained in the vegetative biomass). There is much evidence that, in a given climate, the growth of many crops is directly related to the amount of water they transpire. The explanation is that both carbon dioxide (CO₂) for photosynthesis and transpiration occur concurrently through the same stomatal openings in the leaves, so the two processes should be roughly proportional.

In actual practice, however, the volume of water reported to be consumed in the field consists of evapotranspiration rather than of transpiration alone. Evapotranspiration includes, in addition to the amount of water transpired by the plants, the amount evaporated directly from the soil surface without being taken up by the plants. In addition, evapotranspiration often includes the amount of water intercepted by the foliage (e.g. under overhead sprinkler irrigation) and evaporated without ever entering either the soil or the plant. The reason why the term evapotranspiration is taken to be consumptive use is that, in practice, direct evaporation is difficult to measure separately from transpiration, so the two terms are lumped together merely for the sake of convenience.

Clearly, however, much of the water evaporated without entering the plant is consumed non-productively. Therefore, any method of irrigation that minimizes evaporation (but not transpiration) is likely to increase the efficiency of water utilization by the crop. Some of the irrigation methods described in this publication are capable of doing just that: they introduce water directly into the root zone without sprinkling the foliage or wetting the entire soil surface. Such partial-area irrigation methods offer the additional benefit of keeping the greater part of the soil surface (between the rows of crop plants) dry. This discourages the growth of weeds, that would otherwise not only compete with crop plants for nutrients and moisture in the root zone and for light above ground, but also hinder field operations and the control of pests.

Even with total evapotranspiration considered as consumptive use, field application efficiency in most traditional irrigation schemes is still very low: typically less than 50 percent and often as low as 30...
percent. Excessive application of water generally entails losses due to surface runoff from the field as well as to deep percolation below the root zone within the field. Both runoff and deep percolation losses are difficult to control under flood or furrow irrigation, where a large volume of water is applied all at once. They can, however, be minimized where a controlled volume of water is applied at a slow rate over an extended period of time directly to the root zone.

Even with the best irrigation practices, however, field application efficiency values cannot attain 100 percent. Nor should that be the aim, since a certain fraction of the water applied must be allowed to seep downwards and leach the salts that would otherwise accumulate in the root zone. However, with careful management, field water application efficiency values approaching 90 percent are possible, and values of 80 percent are practicable, by some of the methods described in this publication.

A word of warning is in order at this point. No irrigation method or technology in itself guarantees the attainment of high efficiency. How the system is operated is all important. With poor management, even the most sophisticated system can result in water loss and inefficiency. Only knowledgeable, experienced and caring management can ensure that appropriate irrigation systems achieve their full potential benefits (Figure 8).

---

**FIGURE 8**

Typical crop root distributions

Quite different from strictly technical criteria of efficiency is the physiological index, known as crop water-use efficiency. The relevant measure here is the response of the crop to irrigation, not in percentage terms but as total biomass produced (above-ground dry matter) per unit mass of water taken up by the crop. Since, as mentioned above, well over 90 percent of the water taken up by plants in the field is normally transpired, crop water-use efficiency is in effect the reciprocal of what has long been known as the transpiration ratio. The latter is defined as the ratio of the amount of water transpired to the amount of dry matter produced (tonnes per tonne). That ratio can be of the order of 1 000 or more in a dry climate of high evaporative demand.

An alternative way to characterize crop water-use efficiency is in terms of the marketable crop produced per unit volume of water. This expression is identical to the above-ground biomass in the case of crops grown and harvested for forage, but it is quite different where the marketable product is only the fruit, seed or fibre. Generally, but not always, the yield of such products is proportional to total growth, hence also to transpiration.

To maximize crop water-use efficiency, by either of the above criteria, it is necessary both to conserve water and to promote maximal growth. The former requires minimizing losses through runoff, seepage, evaporation and transpiration by weeds. The latter task includes planting high-yielding crops well adapted to the local soil and climate. It also includes optimizing growing conditions by proper timing and performance of planting and harvesting, tillage, fertilization and pest control. In short, raising water-use efficiency requires good farming practices from start to finish.
3.1 Box 1

Summary of ways to improve water-use efficiency

Conservation of water

- Reduce conveyance losses by lining channels or, preferably, by using closed conduits.
- Reduce direct evaporation during irrigation by avoiding midday sprinkling. Minimize foliar interception by under-canopy, rather than by overhead sprinkling.
- Reduce runoff and percolation losses due to overirrigation.
- Reduce evaporation from bare soil by mulching and by keeping the inter-row strips dry.
- Reduce transpiration by weeds, keeping the inter-row strips dry and applying weed control measures where needed.

Enhancement of crop growth

- Select most suitable and marketable crops for the region.
- Use optimal timing for planting and harvesting.
- Use optimal tillage (avoid excessive cultivation).
- Use appropriate insect, parasite and disease control.
- Apply manures and green manures where possible and fertilize effectively (preferably by injecting the necessary nutrients into the irrigation water).
- Practise soil conservation for long-term sustainability.
- Avoid progressive salinization by monitoring water-table elevation and early signs of salt accumulation, and by appropriate drainage.
- Irrigate at high frequency and in the exact amounts needed to prevent water deficits, taking account of weather conditions and crop growth stage.

Finally, all the above indexes of efficiency may be combined in a single concept, the overall agronomic efficiency of water use, \( F_{ag} \):

\[
F_{ag} = \frac{P}{U} \quad (1)
\]

where \( P \) is crop production (total dry matter or the marketable product, as the case may be) and \( U \) is the volume of water applied.

As only a fraction of the applied water is actually absorbed and utilized by the crop, it is necessary to consider the various components of the denominator \( U \):

\[
U = R + D + E_p + E_s + T_w + T_c \quad (2)
\]

where \( R \) is the volume of water lost by runoff from the field, \( D \) the volume drained below the root zone (deep percolation), \( E_p \) the volume lost by evaporation during the conveyance and application to the field, \( E_s \) the volume evaporated from the soil surface (mainly between the rows of crop plants), \( T_w \) the volume transpired by weeds, and \( T_c \) the volume transpired by the crop. All these volumes pertain to the same unit area.

Accordingly:

\[
F_{ag} = \frac{P}{R + D + E_p + E_s + T_w + T_c} \quad (3)
\]

Under flood irrigation as commonly practised in river diversion schemes, excessive water application often results in considerable runoff, evaporation from open water surfaces and transpiration by weeds. In the experience of the author, these losses commonly amount to 20 percent or even 30 percent of the water applied. In addition, the loss of water due to percolation below the root zone may be of the order of 30 percent or even 40 percent of the water applied. Consequently, the fraction actually taken up by the crop is often below 50 percent and may even be as low as 30 percent.
If runoff and direct evaporation of free water are prevented, and if evaporation from the soil surface is minimized (as under partial-area irrigation that avoids wetting the areas between rows) and weeds are effectively controlled; and if, furthermore, water is applied in measured quantities commensurate with crop requirements so as to avoid excessive percolation, all the losses can be reduced to less than 20 percent of the water applied. Irrigation efficiency can then attain or even exceed 80 percent. Finally, and no less important, the numerator of the equation (namely, the yield attainable) can be greatly enhanced by judicious selection of crops and varieties, optimal fertilization and tillage and proper timing of planting and harvesting. All in all, the agronomic efficiency of water use in irrigated farming can be significantly increased relative to the low efficiency characteristic of traditional practice.

Irrigation water, even if it is of high quality, invariably contains some salts, and these are mostly left behind as crop roots absorb water from the soil.

Evaporation may take place from exposed bodies of water in the case of surface irrigation, or from wind-drift and intercepted water in the case of sprinkler irrigation.

The aim of modern irrigation development must be to make the best use of water in conjunction with land and human resources, as well as with all other essential inputs (energy, machinery, fertilizers and pest control measures) so as to enhance and sustain crop production. The selection of an appropriate irrigation technology for any given combination of physical and socio-economic condition involves complex and sometimes conflicting considerations. Where water shortage is acute, the obvious overriding need is to raise the efficiency of water utilization. Where capital is short, the major requirement might be for an irrigation method with minimal dependence on capital investment or expensive equipment. In other cases, the deciding factor may be energy requirements, labour availability or maintenance costs.

Since the economic considerations, along with the physical conditions and cropping patterns, are necessarily specific to each location, an irrigation system that may seem most appropriate in one country or region may not be so in another. In particular, it is a mistake to assume a priori that a modern system proved to work in an industrialized commercial economy will necessarily succeed in the context of an emerging economy.

The following sections describe and compare the various alternatives with respect to their possible applicability in developing countries, particularly in Africa. Physical factors generally involved in system selection include soils, crops, climate, topography, water quality and availability, drainage, field size and general system performance. Human factors include labour and management, training and skills. Economic factors include the costs of labour, capital and energy in relation to expectable returns. Not all of the relevant factors can be defined or weighed quantitatively in each case, so often the decision as to which system to select rests in part on subjective preferences rather than explicit analysis.
Five ways to apply water to crops

1. **Surface irrigation**
   Running or impounding water over the surface and allowing it to saturate the soil to some depth.

2. **Sprinkle irrigation**
   Spraying water into the air and allowing it to fall on to plants and soil as simulated rainfall.

3. **Drip irrigation**
   Dripping water on to a fraction of the ground surface so as to infiltrate it into the root zone.

4. **Subsurface exuders**
   Introducing the water directly into the root zone by means of porous receptacles.

5. **Subirrigation**
   Raising the water-table from below (in places where the groundwater is shallow and controllable) so as to moisten the root zone by capillary action.

There is, altogether, no "best system" for various crops, soils and farm unit sizes. The aim should be not the "best system" but a spectrum of options that may be appropriate for the circumstances. The search for appropriate methods is necessarily guided and constrained by available knowledge as well as by local trial and error.

The first criterion for selecting and adapting one or another of the modern irrigation methods to the special needs and circumstances of developing nations in Africa is to reduce the capital costs associated with the installation of such systems. In the industrialized countries, commercial systems are designed to minimize labour requirements by substituting mechanical power and automation for human labour, and by enlarging the systems so as to achieve economy of scale. In many developing nations, the economic equation is reversed: labour is often more readily available while capital and fuel are in shorter supply. Farming operations are typically carried out by individual farmers or families who generally cannot afford major investments in machinery, especially if such machinery must be imported from distant sources. The appropriate irrigation systems for such farmers should be based, to the extent possible, on self-reliance - that is to say, on local materials and labour. The process of adaptation must also include a downscaling of the system so as to fit the size of a family holding, generally no larger than several hectares and often less than one hectare.

A wide spectrum of options exists for introducing irrigation methods consistent with the principles described. The range of possibilities includes, at one end, systems of water conveyance, distribution and application that can be fabricated entirely locally, of a sort that even small-scale subsistence farmers can adopt them and be self-sufficient in their maintenance. At the intermediate level are systems based in part on manufactured components, preferably of a type that can be fabricated by workshops or factories within each country or region. Only in the special circumstances where high-value cash crops can be produced in a well-developed market economy will systems relying entirely on imported equipment be justified.

In no case can blind acceptance be assumed of any technology or methodology designed and introduced entirely from the outside. Local trial and error (guided, to be sure, by sound basic principles) will be necessary, as systems must be proved in practice to fit the circumstances and preferences of their intended users. Local experience will evolve gradually and will take time to become local expertise. The region's own farmers should be involved from the outset and encouraged to participate and innovate. Local entrepreneurs may then develop the capability to improvise essential components and service irrigation systems.

There can be no short cut to the process of adoption and adaptation; it should not be rushed and must not be imposed from above. Rather, it should be nurtured by means of positive incentives. Extension services can provide information, demonstrations and guidance to farmers where needed, while financial institutions can offer them credit on favourable terms to invest in appropriate irrigation technology. Such technology will only be accepted if it produces adequate returns, that is to say, if its benefits clearly justify the costs. Since the benefits will depend in each case on marketing opportunities and other local factors, they cannot be predicted ahead of time by outsiders.

The **HELPFUL** (High-frequency, **Efficient**, Low-volume, **Partial-area**, Farm-*Unit*, Low-cost) irrigation methods described in this section can be divided into two broad categories: first, below-ground application methods, and second, above-ground application methods.

### 4.2 Box 3
Definition of HELPFUL irrigation
4.3 BELOW-GROUND APPLICATION METHODS

In this group of methods, water is applied directly to the root zone via porous or perforated receptacles that are embedded in the soil to some depth (from 10 to 50 cm), with their openings protruding above the soil surface. These receptacles, which are filled with water periodically or kept filled continuously, exude the water through their permeable walls into the surrounding soil. The moisture applied in this manner feeds the roots of the crop. When arranged in a grid, these embedded applicators produce a pattern of wetting that can be optimized with respect to the spacing and rooting habit of the crop thus irrigated.

The rate of infiltration and the distribution of moisture within the root zone also depend on the properties of the soil itself. For example, in a coarse-textured (sandy) uniform soil profile, the water would naturally tend to flow downwards, thus producing a carrot-shaped zone of wetting. On the other hand, in a fine-textured (clayey) or layered profile, more water would tend to spread laterally in the soil, thus producing an onion-shaped zone of wetting. If cylindrical porous containers are fitted to form a continuous tube that is embedded horizontally in the soil, they can constitute a line-source capable of irrigating an elongated bed. Soluble nutrients (fertilizers) can be injected into the water supply, to enhance the efficiency of fertilizer use as well as of water use by a row crop.

In principle, this type of irrigation can provide water steadily, as long as the receptacles contain water. The frequency with which they must be refilled depends on their capacity (the volume of water they can hold) as well as on the rate of water flow into the soil. The latter, in turn, depends on the permeability of the receptacle walls as well as on the rate of soil moisture extraction by the surrounding root system. If the applied water contains particulate matter (suspended sediment, either mineral or organic), or if it contains precipitable chemicals (such as calcium salts), these may eventually clog the pores of the receptacles. Algal or bacterial growth may also cause clogging. The remedy is to flush out the receptacles periodically with an acidic or fungicidal solution, and to replace them after some time (every few years).

In arid areas, where the upper zone of the soil is not leached by rains sufficiently, subsurface irrigation may cause salt accumulation at the surface, especially if the irrigation water contains an appreciable concentration of salts. Where this occurs, the topsoil must be leached each season by impounding water over the surface prior to planting time.

**Porous ceramic jars**

The use of soil-embedded porous jars is one of the oldest of the partial-volume, high-frequency (or continuous) irrigation methods. Although the origin and antiquity of the method cannot be established with certainty, numerous reports have attested to its use by traditional farmers throughout North Africa and the Near East (Figures 10 and 11).
The method consists of placing porous clay jars (or pots) in shallow pits dug for this purpose. Soil is then packed around the necks of the jars so that their rims protrude a few centimetres above the ground surface. Water is poured into the jars either by hand or by means of a flexible hose connected to a water source. The jars used are generally made of locally available clay, so they are of no standard shape, size, wall thickness or porosity. For best results, the jars should be fired at relatively low heat and without glazing, so they remain permeable. Trial and error experience should lead to the manufacture of jars with optimal properties of strength (to resist crushing), permeability (to exude water into the soil at a more or less steady rate), and size (to hold enough water for at least a one-day supply). The clay jar irrigation method appears to be most suitable for fruit trees, but it can also be used for row crops. For young tree plantations, a single jar placed adjacent to each sapling should suffice initially. For example, if a single 5 litre jar wets a soil volume having an effective cross-sectional area of, say, 1 square metre, and if the rate of exudation is such as to empty the jar within one day, then the supply rate would be equivalent to 5 litres per square metre per day. The pattern of lateral and vertical spreading of the water exuded from each jar depends upon soil texture and profile stratification. It may also depend on the shape of the jars (whether slender and long, or wide and shallow). As each tree grows, its canopy covers a larger area and its roots tend to grow laterally and vertically to tap a larger soil volume. A mature fruit tree whose canopy covers a ground area of about 10 square metres may require roughly 30 to 50 litres per day during the dry summer period. To meet that requirement, the irrigator can place several jars in a circular pattern around the trunk of each tree. The porous jar irrigation method is flexible enough to permit adding porous jars gradually as the trees grow and the need arises for more water per day and for a larger volume of wetted soil. The example given above is hypothetical, of course. The actual amount and rate of water application should be determined in each case in accordance with local experience. Careful observations and trials are needed to optimize the system's controllable variables. The exposed openings of the jars may attract thirsty land animals as well as birds, and these may in turn damage the crop. For this reason, as well as to prevent clods of soil from falling into the jars and reducing their effective volumes, irrigators should cover the tops of the jars between waterings. This can be done simply by placing a stone over each jar. The simplest but most laborious way to fill the jars with water is to do so manually, by using hand-carried buckets fitted with spouts. A more efficient way is to use a flexible hose connected to a water source. A still more labour-saving device for filling the jars is to set a narrow hose in place for the duration of the season, with perforations made over each jar. At appropriate intervals of time (daily or weekly, as the case may be) the hose can be connected to a water source so as to fill all the jars along the line simultaneously. How long the jars last depends on several factors, including the rate of clogging by turbid water (containing suspended clay or organic matter), or by saline water. Acidity of the water as well as of the soil may also affect the durability of the jars, especially if the material from which they are made contains calcareous fragments. Careless trampling by humans or animals may crush the jars or fill them with loose earth. Simple though it is, the porous jar irrigation system must be monitored constantly if it is to be kept in continuous and satisfactory operation.

**Porous and sectioned pipes**
This is a variant of the porous jar method of irrigation, designed to spread water along a continuous horizontal band in the soil, rather than at discrete locations. As such, the porous pipe method is more suitable for closely spaced row crops grown in beds, such as vegetable crops. To allow water entry, the pipe is bent at one end, and the orifice is made to protrude above ground.

A good demonstration of the porous and sectioned pipe method of irrigation has been carried out by the British Institute of Hydrology in southeastern Zimbabwe, in cooperation with the Zimbabwe Ministry of Agriculture and Water Development. They use locally made clay pipes, approximately 24 cm in length and 7.5 cm in internal diameter, with a wall thickness of 2 cm. (These dimensions are arbitrary, of course.) The pipes are placed at the bottom of a shallow trench (about 25 cm deep) representing the centre-line of a 1 metre-wide bed, and are thus arranged to form a continuous horizontal tube, 3 metres long. The trench is then back-filled with earth.

To allow filling with water, an inlet is formed at one end of the pipe by tilting the first pipe section (the lower end of which was slanted during manufacture to fit the second, horizontal section). As the pipe sections are only abutted against one another but not sealed, water can leak into the soil at the joints between adjacent sections as well as through the porous walls of each section (Figures 12-14).

**FIGURE 12**
The pattern of soil wetting under irrigation by means of subsurface porous clay pipes: pipe sections are fitted to form parallel horizontal line sources for irrigating a row crop

**FIGURE 13**
The pattern of soil wetting by a horizontal porous pipe embedded between parallel crop rows

**FIGURE 14**
Planting a crop in rows directly above horizontal porous pipes

Experience shows that a single pipe, so arranged, can irrigate two rows of a vegetable crop, planted on each side of it. The amount of water applied is the equivalent of 6 to 8 mm per day during the
growing season for a crop of rape. Okra and tomato were also grown successfully using this method of irrigation (Murata et al., 1995).

**Perforated plastic sleeves**

An interesting variant of the subsurface exuder method of irrigation is the use of thin plastic sheeting to form a sleeve-like casing. The chief advantage of the method is its low cost. However, the method has several distinct disadvantages that restrict the range of its applicability (Figure 15).

![Diagram of wetting by a sand-filled plastic sleeve](image)

**FIGURE 15**
The pattern of wetting by a sand-filled plastic sleeve, perforated on one side and placed vertically in the root zone

Since the soft plastic material that serves for the making of a sleeve cannot retain its shape, the sleeve must be filled with sand before being placed in the soil. The sand filling reduces the capacity of the sleeve (i.e. the volume of water that it can hold) by some 50 to 60 percent. Moreover, the sand itself tends to retain a significant fraction of the moisture given it and to resist outflow. Thus the effective capacity is reduced still further.

Finally, since the plastic casing is essentially impervious (unlike the porous clay described above), it must be perforated. The need to optimize the diameter and density of the perforations introduces another variable into the system, the best solution to which must be established by trial and error. Too many perforations can weaken the plastic sheath and reduce its life span (which in any case cannot be expected to be as long as a clay jar or tube). In some cases, roots of the crop or of weeds may penetrate the perforations. As a consequence of all these factors, the ability of the sand-filled plastic sleeve to deliver water to the surrounding soil is limited, both in volume and in rate.

Notwithstanding these potential shortcomings, this method has been applied with apparent success to the growing of manioc and other crops in sandy soils in Senegal. To define its comparative usefulness better, however, the method should be tested side by side with alternative methods of irrigation. To date, this has not been done systematically.

**Below-ground drip**

A much more sophisticated and hence more expensive method of subsurface irrigation employs narrow plastic tubes of about 2 cm diameter. These are buried in the soil at a depth between 20 and 50 cm, deep enough so as not to interfere with normal tillage or traffic. The tubes are either porous throughout, or are fitted with regularly spaced emitters or perforations. If porous, the tubes exude water along their entire length. If fitted with emitters, they release water only at specific points. The water so released then spreads or diffuses in the soil. The pattern of wetting depends on the properties of the surrounding soil, as well as on the length of the interval between adjacent emitters and their discharge rates (Figure 16).
A potential problem here is that the narrow orifices of the emitters may get clogged by roots, particles, algae or precipitating salts. Such clogging is difficult to detect as readily as when the tubes are placed over the surface in above-ground drip irrigation. Occasionally injecting an acidic or herbicidal solution into the tubes may help to clear some types of clogging, though the problem may recur periodically. Slit sections of plastic tubes may also be used to cover the emitter and thus inhibit clogging by roots without substantially reducing the discharge rate.

In underground drip irrigation, the delivery of water in the feeder tubes can be constant or intermittent. For uniformity of application, there should be some means of pressure control. If the lines are long or the land is sloping, there can be considerable differences in the hydraulic pressure and therefore in delivery rate, unless pressure-compensated emitters are used. Such emitters tend to be expensive, however.

Experience in Israel, California and elsewhere has shown that this method of subsurface irrigation is feasible in plantations of fruit trees and other perennial row crops. It may also be applicable to annual crops grown in regular beds.

4.4 ABOVE-GROUND APPLICATION METHODS

The methods described in this section are based on the steady or intermittent supply of water to a fraction of the soil surface. This is usually done by delivering the water in closed conduits (e.g. plastic tubes) to specific points, located and spaced in accordance with the configuration of the crop to be grown. At these points, the water is released on to the surface at a rate that, ideally, does not exceed the soil's infiltrability, so the water penetrates into the root zone without any of it either ponding or flowing over the surface.

Closed-conduit (piped) irrigation distribution systems are generally capable of saving water by increasing the uniformity of application and by avoiding losses of both quantity (resulting from seepage and evaporation) and quality (resulting from contamination of water in open channels). But because piped systems require pressurization as well as costly installations, the water is saved often at the expense of increased energy consumption and capital investment. Methods are needed, therefore, that minimize those capital and energy costs.

Full-system drip

Drip irrigation is the slow localized application of water, literally drop by drop, at a point or grid of points on the soil surface. As long as the application rate is below the soil's potential intake, termed infiltrability, the soil remains unsaturated and no free water stands or runs over the surface.

Water is delivered to the drip points via a set of plastic tubes, generally weathering-resistant opaque polyethylene or PVC. Lateral lines, supplied from a field main, are laid on the surface. They are commonly 10 to 25 mm in diameter and are either perforated or fitted with special emitters. The latter are designed to drip water on to the soil at a controlled rate, ranging from 1 to 10 litres per hour per emitter.

The operating water pressure is usually in the range of 0.5 to 2.5 atmospheres. This pressure is dissipated by friction in flow through the narrow passages or orifices of the emitters, so the water emerges at atmospheric pressure in the form of drops rather than a jet or spray.

Commercial emitters are either in-line (spliced into the lateral supply tubes), or on-line (plugged on to the tubes through a hole punched into the tubing wall). Commercial emitters are precalibrated to discharge at a constant rate of 2, 4 or 8 litres per hour. The discharge rate is always affected by changes in pressure, but less so in the case of pressure-compensated emitters. The frequency and duration of each irrigation period are controlled by means of a manual valve or a programmable automatic valve assembly. Metering valves are designed to shut the flow automatically after a pre-set volume of water is applied (Figure 17).
A basic trickle irrigation system (schematic)

Water tends to spread sideways and downwards in the soil from the point where it is dripped. The fraction of the soil’s total volume that is actually wetted depends on the density of the drip points (the grid), as well as on the rate of application and the internal water-spreading properties of the soil. The wetted zone, and hence the active rooting volume, is usually less than 50 per-cent of what would be the normal root zone if the entire soil were wetted uniformly.

Under frequent drip, the wetted portion of the soil is maintained in a continuously moist state, though the soil is unsaturated and therefore well aerated. This creates a uniquely favourable soil moisture regime. Drip irrigation thus offers a distinct advantage over flood irrigation and even over less-frequent sprinkle irrigation, especially for sandy soils of low moisture storage capacity and in arid climates of high evaporative demand. In contrast with sprinkle irrigation, drip is practically unaffected by wind conditions. Compared to surface irrigation, it is less affected by soil texture, topography or surface roughness.

If irrigation is applied in an amount that exceeds crop requirements, the wetted zone under each dripper becomes elongated downwards, and may eventually form a "chimney" draining the excess water beyond the reach of the roots (Figure 18).

With drip irrigation, it is possible to use somewhat brackish water (e.g. with a salt concentration of about 1 000 to 2 000 mg/litre) for the irrigation of crops such as cotton, sugar beet, tomatoes or dates that are not too sensitive to salinity. The brackish irrigation water does not come into direct contact with the foliage, which is therefore not so prone to salt-scorching as in sprinkle irrigation. Because the soil in the wetted zone is kept constantly wet, the salts are prevented from concentrating and the
salinity of the soil solution in the rooting zone does not significantly exceed that of the irrigation water. If the irrigation water is brackish, however, a fraction of the salts carried by the water tends to concentrate at the peripheries of the wetted circles, forming visible rings of salt around each drip point. In areas that receive appreciable seasonal rainfall, such salt rings are usually leached away annually. Full-system drip irrigation can greatly reduce labour costs, but its successful operation demands constant supervision by skilled technicians with a ready supply of spare parts. It is certainly not a system that, once installed, can continue to operate trouble free by itself. Drip emitters must be inspected regularly and cleaned or replaced whenever any fail by clogging or mechanical damage. Though the plastic tubing used in drip irrigation is weathering-resistant and flexible, it is vulnerable to kinking and cracking when bent or trampled repeatedly, as well as to puncturing by tillage implements, rodents and birds. Burying the tubes in the ground increases their longevity but makes them harder to inspect and to repair when they are damaged.

The most important aspect of drip irrigation maintenance is the prevention of clogging by suspended particles (silt), by biological organisms or their products and by chemical precipitation of salts. Algae and other biological slimes can be controlled by chlorination. Special care is needed where the irrigation water is drawn from open reservoirs that are turbid with silt and greenish with aquatic plants. Salts such as calcium carbonate can be prevented from precipitating by acidifying the water periodically.

Particles of various sorts can be removed from the irrigation water by means of screen filters, media filters (containing gravel, sand or diatomaceous earth) and centrifugal separators. Filters of one kind or another are, in fact, integral components of drip irrigation systems. Screen filters are rather delicate and require frequent inspection and servicing. Gravel and sand filters are less expensive, but tend to be bulky and to result in considerable loss of pressure. As the pores of the gravel or sand medium become clogged with retained solids or slime, pressure loss increases and flow rate diminishes, so these media require frequent back-flushing and periodic replacement.

The spacing between lateral tubes is determined by the spacing of the crop rows, as these tubes are generally laid alongside each row. In crops with closely spaced rows, it is often possible to economize in tubage requirements by using a skip-row arrangement or by placing a single lateral tube between a pair of close rows grown on a bed. This is not possible, of course, in the case of widely spaced shrub or tree crops. In principle, drip irrigation is most suited to orchard crops and to garden crops grown in rows and beds, and least suited to close-growing field crops requiring uniform wetting of the entire soil volume (Figure 19).

![Figure 19](image-url)

**FIGURE 19**
The pattern of soil wetting under drip emitters placed either side of a tree

The capital investment costs of drip irrigation systems are relatively high because large quantities of pipes, tubes, emitters and ancillary devices are necessary to control the precise delivery of water to specific sites in the field. Moreover, since standard drip-emitter orifices are narrow, expensive filtration equipment is necessary to prevent clogging. Hence drip systems tend to be more expensive, at least initially, than surface irrigation. Drip systems may prove to be economically justifiable in the long run if they can indeed prevent the waste of water and the degradation of land that is so frequent under traditional irrigation. However, to make drip irrigation more applicable to African conditions, ways must be sought to simplify the system and make it less expensive to install and operate.

**Simplified drip**
The highly sophisticated equipment developed to serve drip irrigation systems in the industrialized countries obscures the concept's essential simplicity. The main justification for such a capital-intensive and generally energy-intensive approach is to reduce the costs of labour. Since the relative costs involved in the promotion of irrigation for the developing countries of Africa are often the reverse of those in the industrialized countries, consideration must be given to simplifying drip irrigation systems. Efforts must be directed towards redesigning drip systems so as to facilitate installation and maintenance, while retaining the basic principles of high-frequency, high-efficiency and low-volume irrigation (Figures 20-24).

**FIGURE 20**
An on-line point-source emitter with a single dripper

**FIGURE 21**
An on-line emitter with multiple drippers

**FIGURE 22**
Section of an in-line emitter with capillary spiral flow path, and of an on-line (plug-in) narrow-orifice emitter
FIGURE 23
The patterns of spreading moisture under drip irrigation in sandy, loamy and clayey soils

Drip emitters need not necessarily be precision-fabricated. Instead, they can be improvised by punching holes manually in the lateral tubes. To make such perforations as uniform as possible, the use is recommended of standard round-edged cutters of the type used for leather belts. To prevent excessive outflow or blockage of the perforations, users can cover the holes with tight-fitting collars made by slitting short sections of the same tubage that is used for the laterals and slipping them over the holes. With trial and error experience, a user can make adequate emitters for a fraction of the cost of commercial emitters. Moreover, such emitters are easy to service, i.e. to clean or unclog whenever necessary. Another way to make emitters is to insert sections of microtubes into holes punched in the lateral tubes, then adjusting the microtube length to provide the desired discharge rate (Figures 25 and 26).

FIGURE 24
A method of promoting the penetration of water into tight sloping ground under drip irrigation by means of a gravel-filled ring driven into the soil to a depth of several centimetres

FIGURE 25
Making a simple drip emitter by perforating a plastic tube and covering the perforations with a sleeve cut from the same tube
Hydraulic pressure in the delivery lines need not be created by means of mechanical pumps. Elevating the reservoir just a few metres above the land to be irrigated may create a gravitational head sufficient for drip-irrigating a small area. Larger-diameter tubes and wider emitter orifices, as well as longer durations of irrigation, can compensate for the lower operating pressure. The need for precision pressure-regulators is thereby obviated, especially where the land is fairly level and the laterals are not too long or narrow.

Filtration can be accomplished by interposing a simple sand-filled container between the source of the water and the irrigation lines. Incoming (turbid) water can be introduced at the bottom of the container and made to flow upwards through the layered sand, so that the filtered water collects on top and overflows into the irrigation lines. Such a filter can be assembled locally, using either a metal or a plastic container of whatever size is found to be adequate for the flow rate and the turbidity of the water. The sand to be used should be pre-washed to remove the finer particles, and it should be rewashed or replaced at regular intervals as it gradually tends to clog.

Measurement of flow is an essential requirement of efficient water use. Where a system is not equipped with flow meters or metering valves, the flow must be monitored by recording the duration of each irrigation. The volume of discharge per unit time should be checked and rechecked periodically, as should be the uniformity (or variability) of emitters within each lateral line and of the lines within the field. This can be done by recording the time needed for the discharge to fill a vessel of known volume. The volume of water in each irrigation application should conform to the estimated irrigation requirement for the crop, given its stage of growth and weather conditions (rainfall and evapotranspiration since the previous irrigation).

Microsprayer

Microsprayers, also called mini-sprinklers or spitters, are similar in principle to drip systems in that water is applied only to a fraction of the ground surface. However, instead of dripping water from narrow-orifice emitters, microsprayer systems eject fine jets that fan out from a series of nozzles. Each nozzle can water an area of several square metres, which tends to be much larger than the individual areas wetted by single drip emitters. Microsprayers can thus help to enlarge the volume of soil available for the uptake of water and nutrients by crop roots (thereby obviating the need for multiple drippers). Enlarging the wetted volume is especially important for large trees (Figure 27).
Another significant advantage of microsprayers over drip systems is that, thanks to the larger nozzle orifices and the greater rate of discharge, the hazard of clogging is reduced and the filtration requirements are not as stringent as in the case of drip irrigation. For this reason the installation costs may be somewhat lower. The pressure requirements, however, remain in the order of one to two atmospheres - lower than those for regular sprinklers but still requiring pumpage or a commanding reservoir elevation of 10 metres or more.

In other respects, microsprayer irrigation retains the potential benefits of drip irrigation: it permits high-frequency, low-volume irrigation as well as the injection of fertilizers into the water supply. Moreover, microsprayer systems can be scaled down readily to accommodate the small irrigation units prevalent in developing countries.

The disadvantages of microsprayer irrigation relative to drip irrigation must also be considered. The evaporation component of the water balance is increased because of the larger wetted area of ground, the spraying of water into the dry air and the wetting of the lower foliage of the crop. Because of the wetting of leaves, the use of brackish water and the incidence of fungal diseases can be more problematic with microsprayer irrigation than with drip.

Microsprayer systems are served by the same tubing network as drip systems. A wide variety of emitter units, generally made of durable plastic materials, is now available commercially. Such spray nozzles are harder to improvise, however, so the irrigator in this case must depend on manufactured components more than in the case of the simplified drip system described above.

**Low-head bubbler**

Bubbler irrigation is a partial-area, low-volume, high-frequency irrigation method based on closed-conduit delivery. It is designed to reduce investment and energy requirements by using inexpensive, thin-walled, corrugated plastic pipe of sufficient diameter that even the limited pressure available from a low-head surface reservoir might suffice. Bubbler irrigation is essentially a modification of drip irrigation, intended to make the system less dependent on industrially produced components (Figure 28).
commercial product by equipment salesmen. Perhaps this is the reason why so many potential users are unaware of its advantages, including its low cost and its ease of installation and operation. A procedure for installing and calibrating bubbler systems was described nearly 20 years ago by Rawlins (1977). Since that time, experience by the author of this publication and others has proved the system to be practical. Such systems, or variations of them, can serve as attractive options for tree crops, particularly on relatively level lands that can be converted from rain-fed farming or from traditional surface irrigation methods.

**Fertilizer injection**

Many soils in Africa are inherently low in fertility. Soils of the humid tropics tend to be highly leached and in places exhibit acidity, as well as aluminium or sulphate toxicity. Soils of the arid subtropics are typically coarse-textured and have low organic matter content. Such soils often require chemical amendments, manuring or fertilizing if they are to provide the higher yields needed for food security. Conventional methods of applying fertilizers, as by broadcasting uniformly on the surface or by drilling a continuous band of fertilizer alongside the row crop, are not compatible with partial-area or partial-volume irrigation. For best results, the spatial distribution of the fertilizer in the soil should correspond to the distribution of the water. Where water is applied only to a fraction of the soil volume, crop roots concentrate in the wetted portion of the soil. It is important, therefore, to ensure that the restricted rooting zone be endowed with the nutrients essential for crop growth. Surface application of dry fertilizer may not ensure optimal placement, especially in the case of below-ground irrigation methods. Experience has shown that fertilizer-use efficiency, as well as water-use efficiency, are enhanced when the nutrients are applied in the irrigation water.

The combined application of water and fertilizers has come to be known as *fertigation*. As such, it is a particular variant of the more inclusive concept of *chemigation*, by which different agrochemicals are introduced into the rooting zone in solution form via the irrigation system. Among the other types of chemicals similarly applied are selective herbicides to suppress weeds, fungicides to control fungal diseases and nematocides to protect crop roots against parasitic nematodes.

In closed-conduit irrigation systems, fertigation can best be accomplished by means of a fertilizer injection tank connected to the main line (Figure 29). A fertigation unit is relatively easy to assemble. It requires no specialized equipment, merely a container of appropriate volume (20 to 100 litres), preferably of corrosion-resistant material, through which the water supply is made to flow. The container should have a wide opening for pouring in and mixing the fertilizer and a watertight seal for it. For systems requiring filtration, such as drip or microsprayer, the fertilizer tank should precede the filter so that any insoluble particles originating in the tank are prevented from clogging the emitters.

**FIGURE 29**

A fertilizer-mixing tank for injecting soluble nutrients (*fertigation*) into a closed-conduit irrigation system

Of the essential plant nutrients, the one most often deficient is nitrogen, whose mineral forms (e.g. ammonium sulphate, ammonium nitrate, potassium nitrate and urea) are generally readily soluble. Applications of nitrogen often result in dramatic bursts of foliar growth and greening, especially in plants growing on leached soils of low organic matter content. However, crops given only nitrogen may soon exhibit deficiencies of the other major elements (phosphorus and potassium), as well as of several minor elements. Potash, when required, is also available in soluble formulations, including potassium chloride, sulphate or nitrate. Fertilizers containing phosphorus may need to be acidified to make them readily soluble. In
tropical soils of very low fertility, deficiencies of minor elements may call for foliar application by spraying.

**Subirrigation by groundwater control**

Subirrigation is the supply of water to the root zone of crops by artificially regulating the groundwater-table elevation. The method can work where the water-table is naturally high, as it frequently is along river valleys or in plains underlain by impervious strata (Figure 30).

![Open ditch](image)

**FIGURE 30**

*Raising or lowering the water-table for subirrigation, by controlling the level of water in parallel ditches*

Open ditches are usually dug to a depth below the water-table, and the level of the water is controlled by check dams or gates. In this manner, the ditches can serve either to drain excess water and thereby lower the water-table during wet periods, or to raise the water-table during dry periods and thereby wet the root zone from below.

The disadvantage of open ditches is that they interrupt the field and interfere with tillage, planting and harvesting. They also take a significant fraction of the land out of cultivation. An alternative is to place porous or perforated pipes (now generally consisting of corrugated plastic tubes) below the water-table, with controllable outlets. When open, the outlets serve as drains; when closed, they allow the water-table to rise. Subsoil pipes are, however, more expensive to install and more difficult to maintain, as they tend to clog with soil or with precipitated iron oxide.

Subirrigation may be used for field crops and pasture, as well as orchards. It is best suited to hydrophilic crops such as sugar cane and dates. The uniformity of irrigation depends on how level the land surface is and how uniform the soil.

### 4.5 Box 4

**Summary of small-scale irrigation methods**

- **Methods based entirely on local materials and workmanship**
  - Low-fired porous ceramic pots are placed on the surface or embedded in the soil within the root zone. When filled with water and dissolved fertilizers, the permeable clay receptacles ooze water and nutrients into the soil.
  - Sectioned ceramic pipes constitute line sources that feed elongated beds.

- **Methods based on imported materials but local fabrication**
  - Moulded plastic pipes or extruded plastic tubing are perforated manually and lain over the ground to simulate drip irrigation.
  - Vertical sections of plastic pipes (or even discarded plastic containers such as bottles) are embedded in the ground.
  - Thin-walled plastic vessels are filled with sand or gravel to provide mechanical resistance to crushing.
  - Slit plastic sleeves cover the perforated sections of the tubes to prevent root penetration into the outlet holes.
• Sand filters prevent suspended particles or algae from clogging the outlets.
• Auxiliary containers are used to dissolve and inject fertilizer into the irrigation water.
• Vertical standpipes are used to deliver water from an underground pipe to small basins.

**Methods based on imported components**

• Manufactured drip emitters and microsprayer assemblies are carefully supervised and maintained.
• Ancillary equipment such as screen and media filters, metering valves, pressure regulators and fertilizer injectors are used in various combinations.

* These options will be justified only for cash crops in a stable market economy.

Precise control of shallow groundwater is a delicate and difficult task, and it involves some serious hazards. The optimal depth of the water-table is some 30 to 60 cm below the root zone. A higher water-table tends to waterlog the soil, restrict aeration and cause capillary rise and evaporation at the surface, where salts can accumulate. On the other hand, keeping the water-table too low may deprive the crop of essential moisture. As the crop grows, its rate of moisture extraction increases and its root system extends downwards, so the water-table tends to fall, unless it is purposely maintained at a high level.

Since the water source is below the root zone, the supply to the roots occurs by capillary action. Hence the operation of the system depends on the sorption characteristics of the soil. A fine-textured (clayey) soil tends to become waterlogged and to restrict aeration. Clay soil also slows the flow of water both in subirrigation and in drainage. Such a soil requires closer spacing of the ditches or of the underground pipes. On the other hand, a coarse-textured (sandy) soil may retain too little water and tend to dry out excessively. As in other modes of irrigation, there can be no substitute for local experience in water control, based on knowledge of the specific soil conditions and crop requirements.

5 Chapter 5: Simple estimation of crop water requirements

Irrigation scheduling is the term used to describe the procedure by which an irrigator determines the timing and quantity of water application. Accordingly, the two classical questions of irrigation scheduling are: when to irrigate? and, how much water to apply?

In conventional low-frequency irrigation by surface flooding or sprinkle methods, the answer to the first question is generally: when the reservoir of available soil moisture in the root zone is nearly depleted. In practice, that implies: when the crop is near the point of experiencing distress. With high-frequency irrigation, in contrast, the farmer need no longer worry about when soil moisture is depleted or when plants are about to suffer thirst. Such situations can be avoided entirely. To the old question, when to irrigate? the irrigator can now answer: as frequently as possible, even daily. To the second question, how much water to apply? the answer is: enough to meet current evaporative demand and to prevent salinization of the root zone.

The evaporative demand is a variable imposed by weather conditions, which fluctuate over time. It can be determined by monitoring relevant weather variables (e.g. temperature, wind, atmospheric humidity and solar radiation) and then applying any of several functional equations or formulae to calculate the potential evapotranspiration (Figure 31 and 32).
FIGURE 31
Weather variables affecting evaporation, transpiration and soil moisture uptake by roots

FIGURE 32
Radiation and water balances on a plant under localized irrigation
Alternatively, and more simply, the evaporative demand can be estimated from the evaporation rate measured directly by means of a standard evaporimeter. One of the simplest and most useful of such devices is the evaporation pan. It consists of a shallow water-filled container that is placed on the ground within the irrigated area. The amount evaporated daily can be obtained conveniently by measuring the volume of water per unit area of the pan that has to be added to the pan to bring the
water surface back up to a marked level. The pan evaporimeter gives an indication of the integrated effect of radiation, wind, temperature and humidity on evapotranspiration from an open field (Figure 33).

![Image of a pan evaporimeter](image)

**FIGURE 33**

*The standard Class A pan evaporimeter, developed by the US Weather Bureau*

Of the various standardized pans, the one used most widely is the Class A pan, introduced by the United States Weather Bureau. It is a circular container, 121 cm across and 25.5 cm deep, placed on a slatted wooden frame resting over the ground. The pan is filled with water to a height about 5 cm below the rim. This standard design is relatively easy to follow, yet it is not critical to do so precisely. Any configuration that does not differ too radically from the Class A pan will, in the experience of the author, give nearly the same results. However, while inexpensive and easy to install, maintain and monitor, evaporation pans do have several shortcomings.

Although a crop field responds to the same climatic variables as does water in a pan, it does not necessarily respond in the same way. A vegetated surface generally differs from a free water surface in the reflectivity, thermal properties (heat storage), day-night temperature fluctuation, water transmissivity and aerodynamic roughness of the plant canopy. Such factors as the colour of the pan, depth and turbidity of the water and shading from nearby plants can all affect the measurement to some degree.

Pan evaporation depends on the exact placement of the pan relative to wind exposure. Pans surrounded by tall grass may evaporate 20 to 30 percent less than pans placed in a fallow area. Rainfall may occur during the irrigation season and may add water to the pan, or thirsty animals wandering in the area may drink from the pan, thus detracting from its usefulness. To avoid water loss to drinking animals (especially birds), pans are often covered by screens. This may reduce the evaporation rate by some 10 to 20 percent, thus requiring the use of a correction factor.

All these shortcomings notwithstanding, pan evaporimeters, if properly sited and maintained, can be useful insomuch as they tend to correlate with other measurements of potential evapotranspiration (PET). The problem is how to translate pan evaporation into an estimate of the crop's PET, and in turn into actual irrigation requirements.

The first step is to apply a correction factor to account for the fact that free water generally evaporates more than does a crop stand, even if that stand is dense, well endowed with soil moisture and is transpiring at its full potential rate. Many experiments have shown that the appropriate correction factor can vary from 0.5 to 0.85. In the experience of the author, based on direct measurements as well as a review of the literature, that factor is typically about two-thirds (say, 0.66):

\[ \text{PET}_{\text{full cover}} = 0.66 \times E_{\text{pan}} \]  

(4)

The second step is to account for the stage of the crop's growth, as indicated by its fractional ground cover. That can be estimated from ground observations of the area shaded by the crop. Since the potential evapotranspiration, while a function of the crop's coverage, is not simply proportional to it, it is proposed here to use the following empirical relationship:

\[ \text{PET}_{\text{partial cover}} = 0.33 \left( 1 + C \right) E_{\text{pan}} \]  

(5)

where \( C \) is the fractional ground cover of the crop, varying from 0 (when the crop is first sown or planted) to 1 (when the crop stand is full). In the latter case, equation (5) becomes equation (4).

The third step is to estimate the irrigation requirements (I), including the actual crop water requirement (W), plus a leaching fraction (L), minus the rainfall that occurred since the previous irrigation (R).
Assuming that the actual crop water requirement is about 80 percent of PET and that the desirable leaching fraction is 10 percent of PET (i.e. \( W = 0.8 \) PET, \( L = 0.1 \) PET), the result is:

\[
I = (0.33 \times (W + L)) \times E_{\text{pan}} (1 + C) - R \\
= (0.33 \times 0.9) \times E_{\text{pan}} (1 + C) - R \\
= 0.3 \times E_{\text{pan}} (1 + C) - R
\]

(6)

These relations should only be regarded as preliminary estimates. Actual field measurements of specific crop responses to varying amounts of irrigation under local conditions should provide more reliable guidance on optimal irrigation amounts. Furthermore, the estimates above refer only to a crop’s active growth stages. As a crop reaches maturity and its tissues become senescent, its water requirements naturally diminish. Irrigation is discontinued when its further contribution to crop yield no longer justifies its added cost.

Potential evapotranspiration (PET) has been defined as the volume of water per unit area of field evaporated and transpired by a dense stand of actively growing short grass that is well endowed with (never short of) water. Actual evapotranspiration (AET) is usually less than PET, as a real field may not be uniformly dense and well watered (Penman, 1948; Monteith, 1980).

6 Chapter 6: Environmental aspects of irrigation development

Irrigation development may have both positive and negative impacts on the environment. To be sustainable, irrigation must avoid the negative impacts.

The positive aspect of irrigation is that, by intensifying food and forage production in the most favourable lands, it can allow a country to reduce excessive pressure on marginal lands now under rain-fed cultivation or grazing. Such lands are already undergoing a process of degradation (known, in semi-arid areas, as desertification). The transition of people who have subsisted for generations on rain-fed lands to irrigated farming may be a difficult social change. However, change will in any case be unavoidable in areas where land degradation becomes acute. Where the opportunity exists for irrigation development, it can serve as a constructive alternative to either famine or mass migration.

The potentially negative environmental impacts of irrigation development may occur off-site as well as on-site. The off-site effects may take place upstream of the land to be developed, as where a river is to be dammed for the purpose of supplying irrigation water. Another set of problems may be generated downstream of the irrigated area by the disposal of excess water that may contain harmful concentrations of salts, organic wastes, pathogenic organisms and agrochemical residues.

Of most direct concern are the potential on-site impacts. Irrigated lands, especially in river valleys prone to high water-table conditions, typically require drainage. Otherwise, they are subject to the twin scourges of waterlogging and salinization. Because groundwater drainage is a complex, exacting and expensive operation (often more expensive than the initial development of irrigation itself), there is a temptation to start new irrigation projects while ignoring the need for drainage or delaying its installation until it is actually needed. The trouble is that, by the time the need for drainage becomes inescapable, the cost of implementing it may be prohibitive.

A thorough discussion of drainage is beyond the scope of this publication. Suffice it to say here that irrigation developers should be mindful of the potential need for drainage and make provision for it in their plans. At the very least, irrigators in each area should monitor the position of the water-table as it tends to rise, by means of observation wells (piezometers). Sampling the water in such wells will allow monitoring of the quality of the groundwater towards which the leaching fraction of irrigation water percolates. Such monitoring can provide an early warning of the eventual danger of salinization, and can guide irrigation practice towards minimizing that danger. Although small-scale irrigation development is less likely to cause waterlogging and salinization than large-scale development, the danger of land degradation should never be ignored.

7 Chapter 7: Human aspects of irrigation development

Irrigation is not simply a mechanical task of delivering water to crops. It is a human activity and a social undertaking. No consideration of irrigation development should fail to note that, ultimately, the success of every project depends on the quality of the human effort invested in it. Moreover, an irrigation project is not only a system for producing crops but also, and perhaps even primarily, a place for a community of people and families to live healthy lives while working cooperatively and contributing to the food security of their nation (Figure 34).
As in other human activities, the first requirement for success is that the workers engaged in the activity be strongly motivated and committed to the task. The second requirement is that they be properly informed, not merely trained in the performance of routine operations but enabled to understand the fundamental principles of proper irrigation management. An investment in research and in training personnel is even more vital in this respect than an investment in pipes or pumps. The third requirement, of course, is that the irrigation workers be given access to (preferably, an opportunity to acquire) the material inputs necessary for the best performance of their work. One of the worst mistakes that can be made by irrigation developers or managers is to assume an authoritarian role, expecting the workers to obey the instructions handed them from above without question. Depriving intelligent human beings of any personal stake in their own work, and of the challenge and incentive to apply their own creative ingenuity, is a waste of a resource even more precious than soil and water. People who are given a sense of participation, and allowed to reap rewards commensurate with their initiative and contribution, care much more for their work and devote much more of themselves to its success. The incentives offered may be social, administrative,
economic, or, best of all, a combination of all three. The greatest incentive is to allow, indeed to encourage, people and families to work for themselves, in harmony with their neighbours, on their own plots of land and with access to assured supplies of water and other essential means of production. To accomplish this aim, policy-makers and administrative agencies need to resolve a complex set of problems involving land reform and tenure, water rights, and the coordination of resource allocation and utilization among various competing sectors, all of which, however, range far beyond the limited scope of this discussion.

In addition to providing workers with incentives, an irrigation scheme may also contribute to human welfare in a larger sense. Many, perhaps most, irrigation systems in the developing world are used for non-agricultural purposes as well as for raising crops: for domestic water needs, waste disposal, power generation, transportation, fishing and recreation. Some of these needs may interfere or conflict with the basic functioning of the irrigation project, particularly if they are not recognized at the outset and included in the initial planning stages.

One of the most serious problems in irrigation projects is the potential health hazard resulting from the use of open water channels for drinking, bathing, washing of clothes and the disposal of human and animal wastes. It has been said that "wherever water goes, disease follows". Unfortunately, water storage and conveyance structures present favourable breeding grounds for disease vectors (such as mosquitoes and snails) and for pathogens of some of the most debilitating illnesses rampant in the developing world. Among these are schistosomiasis (bilharzia), onchocerciasis (river blindness), malaria, cholera, dysentery and other intestinal diseases. Public health specialists should therefore participate in the design and operation of all irrigation schemes, as well as in the rehabilitation or modernization of existing schemes.

Among factors that may contribute to the control of water-borne diseases are the following:

- concrete lining and shaping of the conveyance and drainage channels to prevent stagnation along the banks (as well as, incidentally, to reduce seepage losses);
- control of riparian vegetation within the channels, to prevent clogging, stagnation and harbouring of diseases;
- protection of the channels from wading animals that may breach the banks and pollute the water;
- control of waste disposal by humans, who must be provided with environment-mentally safe sanitary facilities;
- treatment of the water used directly for human needs (filtration and, where necessary, use of chemicals to control parasites).

All these measures can be carried out most effectively in systems that convey water in closed conduits and that restrict access to storage reservoirs. Such conveyance can also facilitate the adoption of the HELPFUL (high-frequency, efficient, low-volume, partial-area, farm-unit, low-cost) irrigation methods described in this publication.

It can thus be seen that the proper development and management of irrigation is a complex and comprehensive undertaking, requiring attention to much more than hydraulics and agronomy. The design and operation of each irrigation project is necessarily site specific not only because of variable physical and agronomic conditions. A special combination of human and economic factors exists in each case and must be recognized in any attempt to promote or improve the practice of irrigation.

8 Chapter 8: A look back

There was a time when experts in the industrialized countries believed that they had ready-made solutions to the problems of underdevelopment in the so-called Third World. All that was needed, they believed, was to transfer already existing expertise and equipment, and then development and modernization would immediately ensue. Unfortunately, that was a costly fallacy, resulting all too often in the hasty introduction, or even imposition, of systems that were at variance or conflict with the existing environmental, cultural or socio-economic conditions. False starts and faltering initiatives have plagued attempts at technology transfer. Huge investments of resources often led to disappointment and disillusionment.

Most capital expenditures for irrigation in developing countries have been on large-scale projects, in the hope of achieving quick and massive increases in production. Typically, a well-meaning national or international agency would conceive and finance a showcase project, based on elaborate engineering. Experts would be hired from abroad to design the system, then contracting and supplying firms would be engaged to implement the design. Subsequently, the marvel of modern technology would be assembled and demonstrated, with great pride and fanfare. The gap of centuries had been bridged, so it seemed, in a single master stroke. Then the foreign contractors, having done their job and reaped their profits, would disappear. Soon afterwards, the elaborate system would cease functioning,
because of the failure of a single cog or inexpert or uncaring operation. Lack of local resources and the difficulty of obtaining replacements or expertise from abroad, exacerbated by an underpaid and indifferent workforce deprived of incentives, would combine to delay the necessary repairs and to perpetuate the failure. The entire expensive system would then stand idle, a mute monument to inappropriate technology transfer.

A case in point are the large-scale centre-pivot sprinkler systems, prefabricated abroad and assembled in various countries in Africa where the traditional scale of farming, the cost of energy and the availability of equipment and technical services contrast sharply with those in industrialized countries. In many places, these imposing machines have become white elephants.

Most organizations responsible for designing irrigation projects have a strong civil engineering orientation, and therefore have tended to emphasize the design and construction of large-scale water supply systems over the small-scale, on-farm management aspects of irrigation. In some countries, there is still a dichotomy between the agency that is responsible for developing water resources and for allocating and delivering the water via canals, and the separate agency responsible for utilizing the water in the field by local farmers. Often the water resources agency is endowed with greater power, funding and prestige than the on-farm management agency, so the first is unlikely to accept guidance from the second on the proper options for water allocation.

Key decision-makers have tended to favour high-visibility capital projects with impressive works, while neglecting the more modest needs of indigenous farm units, as well as the issues of training and maintenance that are of interest to lower-level personnel without decision-making power. Top-level decision-makers have also tended to harbour unrealistic expectations as to the time required for irrigation development and have tended to be impatient with technical or human constraints. Some have been insufficiently aware that the technology they were trying to transfer from the industrialized countries had evolved in a capital-intensive market economy based on the ready availability of technical services and a complex economic infrastructure. Moreover, financing agencies and corporations serving as contractors have naturally tended to prefer large projects providing for the sale of expensive hardware and services, whereas in reality it is often small pilot projects with major emphasis on human skills and local labour that are more likely to achieve sustainable progress.

9 Bibliography


