More Water for Arid Lands

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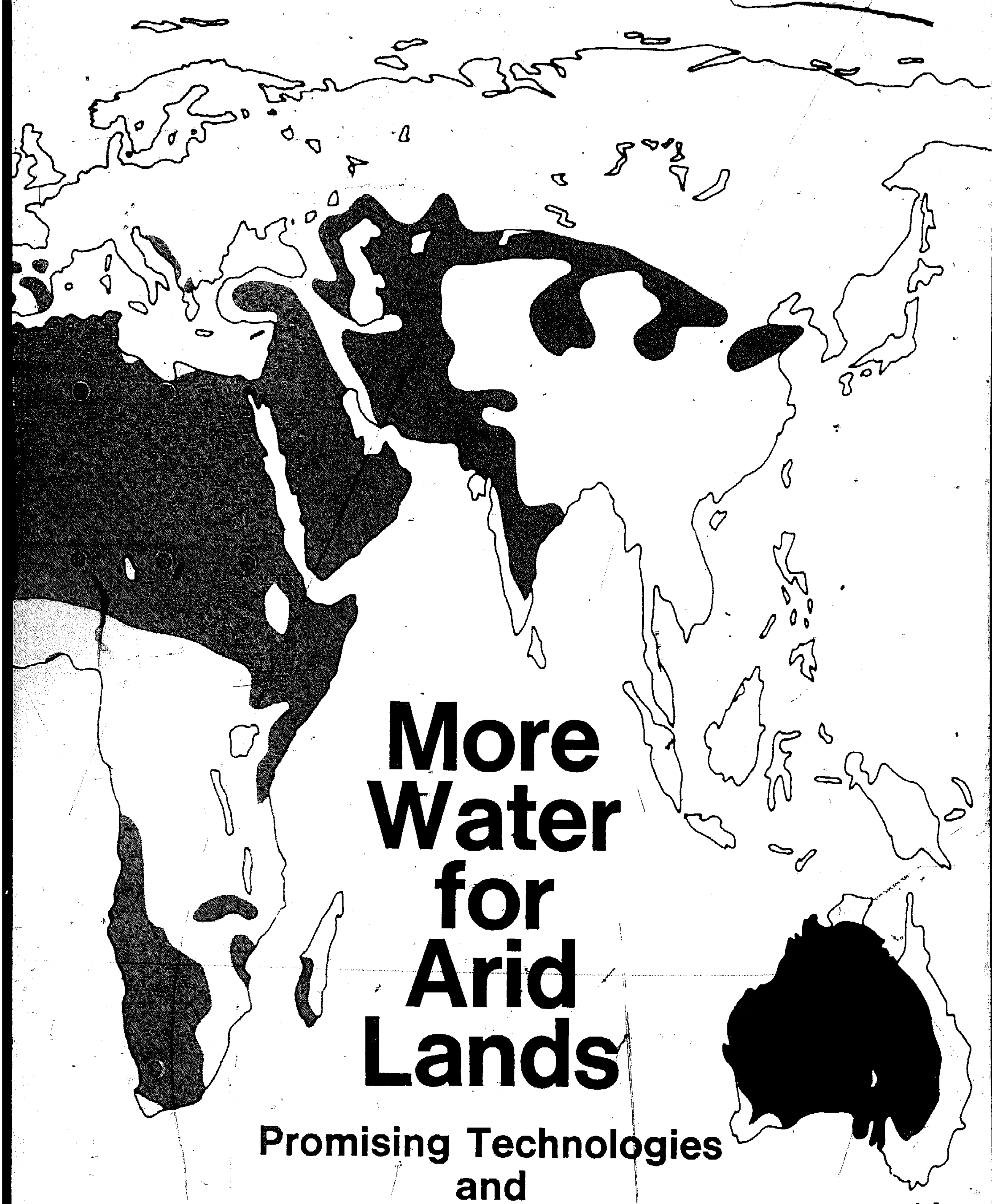

More Water for Arid Lands

Promising Technologies and Research Opportunities

NATIONAL ACADEMY OF SCIENCES

The cover motif highlights arid and semiarid regions where this report may find application. The map is based on a projection developed in 1973 by German geographer Arno Peters. It accurately presents the relative areas of the world's land masses.

More Water for Arid Lands

Promising Technologies and Research Opportunities

Report of an Ad Hoc Panel of the
Advisory Committee on Technology Innovation
Board on Science and Technology for International Development
Commission on International Relations

خلاصه
Résumé en Français
Resumen en Español

National Academy of Sciences
Washington, D.C. 1974

This report has been prepared by an ad hoc advisory panel of the Board on Science and Technology for International Development, Commission on International Relations, National Research Council, for the Office of Science and Technology, Bureau for Technical Assistance, Agency for International Development, Washington, D.C., under Contract No. csd-2584.

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Panel on Promising Technologies in Arid-Land Water Development

DEAN F. PETERSON, Vice President for Research, Division of Research, Utah State University, Logan, Utah, *Chairman*

FALIH K. ALJIBURY, Soil Physicist, Agricultural Extension, University of California, Parlier, California

BAHE BILLY, Executive Manager, Navajo Tribal Agricultural Products Industry, Farmington, New Mexico

C. BRENT CLUFF, Associate Hydrologist, Water Resources Research Center, University of Arizona, Tucson, Arizona

HAROLD E. DREGNE, Chairman, Department of Agronomy, Texas Tech University, Lubbock, Texas

EARL A. ERICKSON, Department of Crop and Soil Sciences, Michigan State University, East Lansing, Michigan

MICHAEL EVENARI, Botany Department, Hebrew University of Jerusalem, Jerusalem, Israel

JEROME GAVIS, Department of Geography and Environmental Engineering, The Johns Hopkins University, Baltimore, Maryland

ROBERT M. HAGAN, Department of Water Science and Engineering, University of California, Davis, California

JACK KELLER, Agricultural and Irrigation Engineering Department, Utah State University, Logan, Utah

FERNANDO MEDELLÍN LEAL, Director, Instituto de Investigación de Zonas Desérticas, Universidad Autónoma de San Luis Potosí, S. L. P., Mexico

LLOYD E. MYERS, U.S. Department of Agriculture, Agricultural Research Service, Western Region, Berkeley, California

SOL D. RESNICK, Director, Water Resources Research Center, University of Arizona, Tucson, Arizona

JAN VAN SCHILFGAARDE, Director, U.S. Salinity Laboratory, Soil and Water Conservation Research Division, A.R.S., U.S. Department of Agriculture, Riverside, California

NOEL D. VIETMEYER, Board on Science and Technology for International Development, Commission on International Relations, National Academy of Sciences–National Research Council, *Staff Study Director*

JULIEN ENGEL, Head, Special Studies, Board on Science and Technology for International Development

Contributors

LEON BERNSTEIN, U.S. Salinity Laboratory, A.R.S., U.S. Department of Agriculture, Riverside, California.

KEITH R. COOLEY, U.S. Water Conservation Laboratory, A.R.S., U.S. Department of Agriculture, Phoenix, Arizona.

ALBERT K. DOBRENZ, Department of Agronomy and Plant Genetics, University of Arizona, Tucson, Arizona.

A. RICHARD KASSANDER, JR., Vice President for Research, University of Arizona, Tucson, Arizona.

L. K. LEPLEY, Office of Arid Lands Studies, University of Arizona, Tucson, Arizona.

MARTIN A. MASSENGALE, Department of Agronomy and Plant Genetics, University of Arizona, Tucson, Arizona.

JAMES J. RILEY, Environmental Research Laboratory, University of Arizona, Tucson, Arizona.

W. T. WELCHERT, College of Agriculture, Cooperative Extension Service, University of Arizona, Tucson, Arizona.

L. G. WILSON, Water Resources Research Center, University of Arizona, Tucson, Arizona.

Preface

Little known but promising technologies for the use and conservation of scarce water supplies in arid areas are the subject of this report. Not a technical handbook, it aims to draw the attention of agricultural and community officials and researchers to opportunities for development projects with probable high social value.

The technologies discussed should, at present, be seen as supplements to, not substitutes for, standard large-scale water supply and management methods. But many have immediate local value for small-scale water development and conservation, especially in remote areas with intermittent rainfall. With further research and adaptation, some of the technologies may prove to be economically competitive with standard methods of increasing the water supply or reducing the demand.

For the convenience of the busy reader, each technology is presented in a separate chapter, and the material is arranged under these topics:

Methods
Advantages
Limitations
Stage of Development
Needed Research and Development
Selected Readings (a short list of reviews and general articles)
Contacts (a list of individuals or organizations the panelists know to be involved in relevant research)

NOTE: Neither the Selected Readings nor the Contacts are meant to be exhaustive.

Several points deserve emphasis:

The panel considers that all the technologies in this report have proved themselves within the individual settings described. When these technologies are applied elsewhere, consideration should be given to unique local conditions that may affect their success. Questions should be asked that cannot all be accounted for in a general report.

The particular choice of technologies examined in the report is not meant to reflect on others, which may be equally worthy of attention. Selection was based on technical merit and potential for application, particularly in developing countries, as seen by the panel. No order of importance is implied by the chapter sequence. Some methods selected are ready for widespread application; for others, the fundamental principles are still being developed. Although most of the ideas discussed are not new, they have as yet had little impact.

In its discussion of the technologies, the panel took heed of their economic parameters but could not consider this subject in specific detail. Attempts to estimate future cost in the vastly different economic and ecological environments of the several dozen countries beset with the problem of aridity would have bogged down the discussions, as would consideration of political, institutional, and social factors. Accordingly, this report confines itself to a technical overview, leaving to the reader the task of weighing the technical prescriptions in the light of his country's resources and capabilities.

The Ad Hoc Panel on Promising Technologies for Arid-Land Water Development formulated this report at a meeting in Tucson, Arizona, in October 1973. Each selected technology was evaluated and written up before the meeting by an individual committee member, in collaboration with the NAS staff; each paper was reviewed by the others, discussed during the meeting, and modified according to the will of the panel as a whole. This document, therefore, reflects a consensus.

The panel is indebted to Tresa Bass and Mary Jane Koob, who acted as administrative secretaries for the meeting and for production of the report, and to A. Richard Kassander, Jr., and Jack D. Johnson of the University of Arizona for local arrangements in Tucson. The report draft was prepared for publication by Jane Lecht, and the Arabic translation by Mohammed Sageer.

This project is part of an experiment to determine ways scientists and engineers can make a more effective contribution to economic-development activities, particularly by translating recent research results into a usable form for decision makers. If you wish to comment on this report and especially if you find it useful in your work, please communicate with the staff officer, Dr. Noel Vietmeyer, National Academy of Sciences – National Research Council, 2101 Constitution Avenue, JH 215, Washington, D.C. 20418, USA.

Two systems of ancient agriculture in the Negev—narrow terraced wadis and farm units with small watersheds—show a most rational and wise use of the available natural resources. The ancient farmer fitted his artificially created agricultural ecosystems into nature and used landscape and topography to his best advantage without damaging his environment. He neither caused erosion nor brought about salination of his agricultural soils. By using the runoff he tamed the flood torrents and prevented the damage that uncontrolled floods usually produce. He certainly did not overirrigate, because his water resources were limited, and in this case as in many others, limitation is the mother of good management. The methods of the ancient civilizations of providing drinking water are another example of a most rational use of nature's resources. The same is true of the [qanat], which merits our special admiration because of the great technical skill and ingenuity involved in its construction. In all these cases man learned from his natural environment and applied what he had observed by imitating nature and sometimes improving on it. This is most obvious in the case of runoff agriculture. Most of the plant associations of the natural desert ecosystems live on runoff water. A good observer will notice this and may apply this knowledge to grow cultivated plants to his own benefit.

Michael Evenari, Leslie Shanan, and Naphtali Tadmor,
The Negev: The Challenge of a Desert.

Part I

Water Supply

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Introduction and Summary

Arid regions today face more difficult problems than ever before. The world's sand deserts appear to be enlarging, and droughts are contributing to the economic devastation of whole nations. The six drought-stricken Sahelian nations provide an extreme illustration, but industrialized and developing countries both suffer from the crisis. The southwestern United States, for example, faces falling water tables and increasing groundwater salinity.

Nevertheless, arid lands have underexploited agricultural potential. We should learn that this potential can be best developed by concepts and methods specifically suited to dry regions. Water practices developed for temperate climates may not work as well in arid regions for technological, environmental, economic, and cultural reasons. We need fresh, innovative approaches to water technologies, particularly those designed to meet the needs of arid regions in the less developed world, where there has often been improper application of practices developed in regions with higher rainfall or more abundant water supplies. Also, we need to reconsider practices developed in arid regions by ancient agriculturalists. Basically, there are two approaches: increasing the supply of usable water and reducing the demand for water. Supply and demand, as well as delivery, have to be considered as an integral system.

There are many possibilities for simultaneously increasing supply and reducing demand that together will bring benefits to arid lands. A major opportunity to save water exists in conventional irrigated agriculture, by far the arid world's largest user of water. This is true for centuries-old, traditional systems as well as for large, capital-intensive modern water-management systems. Conventional systems are not the main topic of this report, because they are extensively treated elsewhere (Selected Readings, p. 5). Still the following points need to be made:

- In some arid lands the greatest opportunity for increasing water supplies is to improve existing water systems and thus make more water available without a complete new installation. For example, replacing canals with closed conduits (of plastic, concrete, metal, etc.) will reduce evaporation, or lining canals will reduce seepage losses. (Most chapters in this report deal in one way or another with improvements to existing water systems and the maximum utilization of existing water supplies.)

- Significant amounts of water can be saved by improving water management on the farm, a topic agriculturalists in many areas often neglect. One deficiency is the design of on-farm distribution and drainage systems between farm fields. Storage, main, and diversion canals and main drains may be well engineered (even down to turnouts serving one or two hundred hectares), but most ditches serving farm fields are inadequate, sometimes even nonexistent. Furthermore, the irrigator often mismanages application of the water.

- In designing new systems and rehabilitating old ones, the needs of the user should be paramount. The system must deliver the right amount of water to the user at the right time. Frequently, an irrigation project fails to reach its potential because the use-requirements for the water have not been sufficiently considered. For example, the delivery system in irrigation should be designed to permit changing the water supply as crop demands change with weather and plant maturity. But water is often delivered in an arbitrary and inflexible manner.

- Where groundwater is available, surface and groundwater supply and delivery systems should be considered in combination (conjunctive use) for optimal use of the total water resource.

- Universally, farmers tend to overirrigate when water is available. This can lead to problems of waterlogging and salinity, and leaching of fertility. Frequently, institutional arrangements (systems of delivery, scheduling, water-rights laws, traditions, etc.) encourage overirrigation. Although overirrigation may be needed to remove accumulating salts, recent studies indicate that the amount required may be much lower than was formerly believed (chapter 3).

- Conventional irrigation is neither cheap nor simple; complexities in the design, construction, and efficient operation of standard irrigation projects are frequently oversimplified or overlooked. Fields are often inadequately leveled, and even small undulations can waste large amounts of water. Precision land-shaping and skilled labor are required. Grading land to a flat surface usually requires high capital costs for equipment, fuel, and maintenance.

- The scarcer the water, the greater the need for technical and management skills.

Chapters 1–6 of this report deal with technologies for enhancing water supplies; the rest cover water conservation. A summary follows of the technologies in this report.

INTRODUCTION AND SUMMARY

Rainwater Harvesting

Rainwater collected from hillslopes and man-made catchments can create new supplies of low-cost, high-quality water for arid lands (chapter 1).

Runoff Agriculture

Runoff agriculture involves rainwater harvesting; the water is used directly in agricultural systems specifically designed for the purpose (chapter 2).

Irrigation with Saline Water

Saline water is widely available but rarely used because it restricts plant growth and yield. Evidence is now accumulating that with care and under certain favorable conditions, saline water can be profitably used for irrigation (chapter 3).

Reuse of Water

Increasing demands on water make it necessary to greatly increase water reuse. Technical developments such as recycling and advanced waste treatment may have great importance in the future (chapter 4).

Wells

Hand-dug wells, a technology begun thousands of years ago, is regaining popularity with the help of new materials and construction equipment. Qanats and horizontal wells, methods for tapping underground water without using pumps, are also described (chapter 5).

Other Sources of Water

This chapter briefly mentions groundwater mining, desalting, solar distillation, the use of satellites and aircraft for detecting water in arid lands, rainfall augmentation, the possibility of using icebergs as a source of water, and dew and fog harvesting (chapter 6).

Reducing Evaporation from Water Surfaces

Because evaporation is invisible, it is seldom regarded as a serious drain on stored water, but annual evaporation losses, particularly in arid lands, are very great. Evaporation reduction merits increased attention as a way to conserve water (chapter 7).

Reducing Seepage Losses

Seepage causes serious water losses in canals and impoundments. Modern materials and techniques can reduce or eliminate seepage, but costs are still high (chapter 8).

Reducing Evaporation from Soil Surfaces

Water losses resulting from evaporation from soil surfaces can be reduced by covers or mulches. In many cases the covers also serve complementary functions such as stopping desert encroachment or promoting runoff agriculture (chapter 9).

Trickle Irrigation

This newly developed irrigation method uses a system of plastic pipes placed on the soil among the plants. Water carried in the pipes drips onto the soil beside each plant at a rate carefully matched to the plant's needs. Compared with conventional irrigation, excellent crop yields have been obtained with a minimum amount of water (chapter 10).

Other Innovative Irrigation Methods

Some simple irrigation methods, neglected in technical manuals or textbooks, with potential benefit for arid lands are presented pictorially (chapter 11).

Reducing Cropland Percolation Losses

Large areas of sandy soil in arid lands are not used for agriculture because the water sinks below the root zone too rapidly and the extra irrigation water needed to compensate for this problem is not available. Techniques are now being developed to produce artificial underground moisture barriers to prevent or restrict water and nutrients from percolating away (chapter 12).

Reducing Transpiration

About 99 percent of the water absorbed by plant roots is released into the air from leaf surfaces. If practical means to reduce this process can be found, major savings can be realized in the amount of water needed to raise a given crop (chapter 13).

Selecting and Managing Crops To Use Water More Efficiently

Relatively little has been done on designing water-efficient systems for arid-land agriculture. Numerous research opportunities from plant genetics to engineering remain to be explored (chapter 14).

Controlled-Environment Agriculture

When crops are grown within watertight but transparent enclosures, the amount of water normally lost can be greatly reduced, and the atmosphere around the plants can be manipulated to maximize productivity. These are costly systems, but high agricultural productivity can be achieved with small amounts of water in very inhospitable regions (chapter 15).

Other Promising Water-Conservation Techniques

This chapter briefly mentions water-conserving soil amendments and artificial recharge of groundwater. (chapter 16).

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1 Rainwater Harvesting

Though rain falls infrequently in arid lands, it comprises considerable amounts of water; 10 mm of rain equals 100,000 l of water per ha. Harvesting this rainwater (FIGURE 1) can provide water for regions where other sources are too distant or too costly, or where wells are impractical because of unfavorable geology or excessive drilling costs. Rainwater harvesting is particularly suited to supplying water for small villages, schools, households, small gardens, livestock, and wildlife.

Ancient desert dwellers harvested rain by redirecting the water running down hillslopes into fields or cisterns (FIGURES 2–4). Modern farmers in arid lands have seldom harvested rainwater in this direct way, though in 1929 a 2400 m^2 catchment in an arid part of Australia (300 mm average annual rainfall) provided adequate water for "6 persons, 10 horses, 2 cows, 150 sheep" even during the years of lowest rainfall.[1]

Today, researchers are working to increase water runoff by modifying the surface of the soil.

Methods

Rainwater harvesting is possible in areas with as little as 50–80 mm average annual rainfall. This seems to be the lowest limit, but during a year with only 24 mm of rain, a water-harvesting catchment in Israel still yielded a usable runoff.[2] In some arid regions, such as the southwestern United States, snow and sleet also contribute to runoff water. Loess and loess-like soils, present in most deserts, are ideally suited for rainwater harvesting because after even a small rainfall they form a crust that promotes runoff.

Sometimes rainfall runoff can be collected from an untouched natural catchment; one way is to dig ponds in small depressions where they can collect runoff (for example, the pond in FIGURE 48, page 84). Often the catchment needs modification, usually by making the soil surface more

[1] Kenyon. 1929. (See Selected Readings.)

[2] Evenari, Shanan, and Tadmor. 1971. p. 325. (See Selected Readings.)

FIGURE 1 The yield from rainwater harvesting can be surprising. Here in the Negev Desert runoff collected from the background hills is channeled to the farm site and distributed to separate fields. (N. Tadmor)

impermeable to increase the amount of runoff. There are many methods, including the following:

Land Alteration

In some cases all that is needed to collect and convey runoff water are ditches or rock walls along hillside contours (FIGURES 2 and 5). Clearing away rocks and vegetation usually increases runoff water (FIGURES 3 and 4); compacting the soil surface can increase it, too (FIGURES 6 and 7).

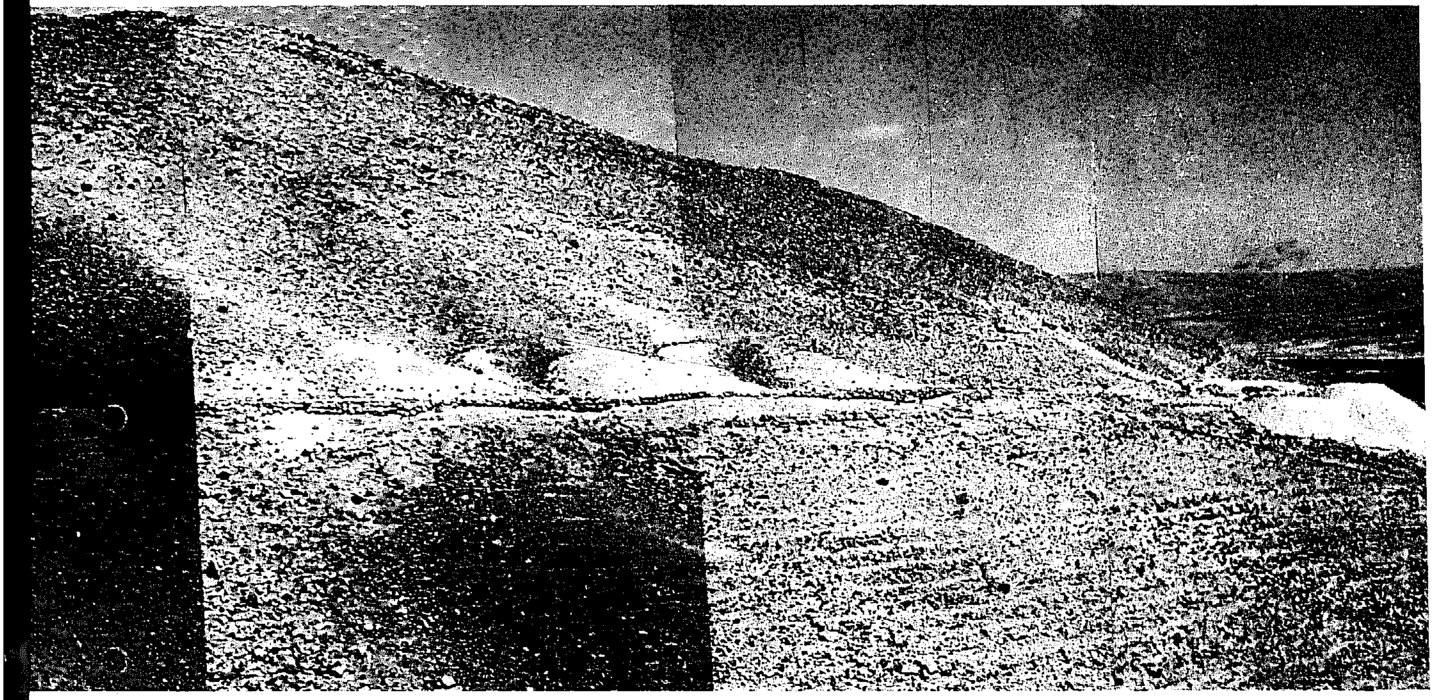

FIGURE 2 Two thousand years ago Nabatean inhabitants of the Negev Desert built this channel across a hillside to harvest rainwater runoff. The channel leads water to a cistern at the right. A similar channel, disappearing to the right, drains the slopes on the other side of the hill. (L. Evenari)

FIGURE 3 Ancient rainwater-harvesting system in the Negev. Gravel that covered the slopes has been moved aside, leaving a catchment that directs rainfall runoff to a farm in the valley. (M. Evenari)

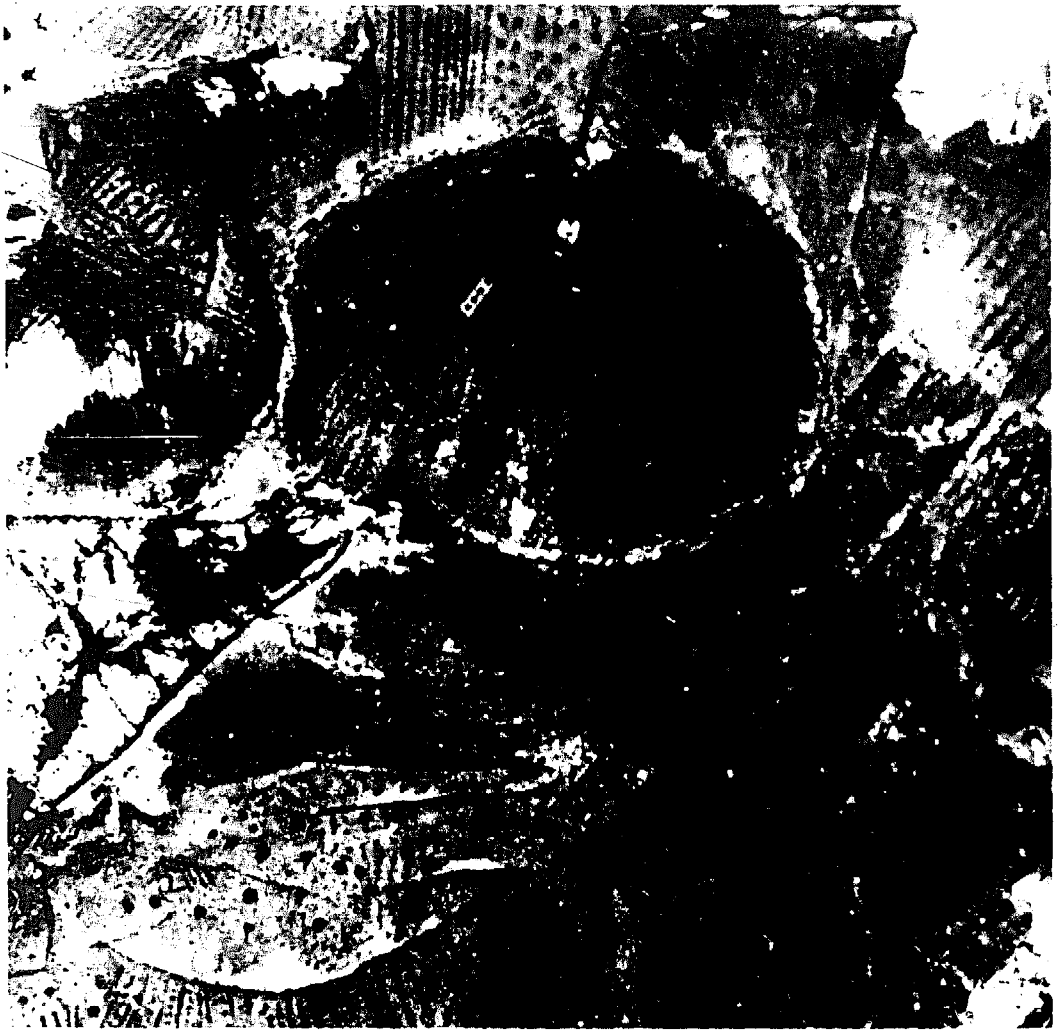

FIGURE 4 Aerial view of ancient gravel mounds and strips still used to increase the rainwater harvest from hillsides in the Negev. Unable to remove all the gravel, the Nabateans mounded it (shown by dots). Conduits and channels are organized so that each drains a small catchment. This system divides overall runoff into small streams, thereby avoiding erosion and presenting the farmer with small, easy-to-handle flows. (N. Tadmor)

With these simple systems erosion is the main problem; when it is not excessive and low-cost hillside land is available, these land alterations can be very economical ways to harvest rainwater in arid lands.

Chemical Treatment

A promising method for harvesting rainwater is to treat soils with chemicals that fill pores or make soil water repellent.

Sodium salts, which cause clay in the soil to break down into small particles (partially sealing the soil pores and cracks), can be used to increase

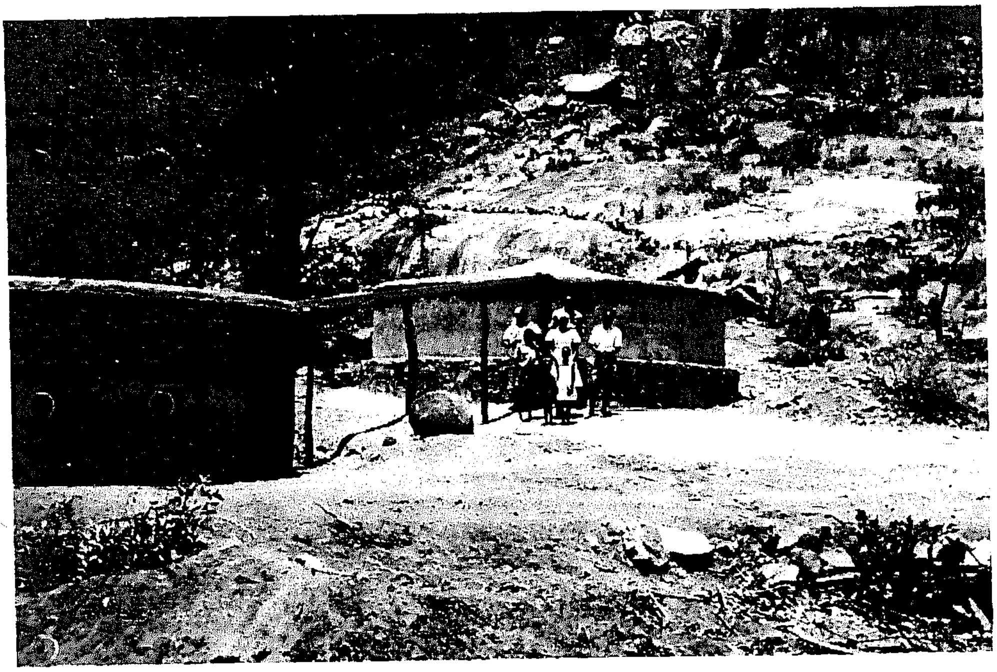

FIGURE 5 Harvesting runoff from rocky hill slopes. Total capacity of the two tanks is 110 m³; 75 mm of rainfall fills both tanks. Rowa African Purchase Land, Rhodesia. (Rhodesia Agricultural Journal)

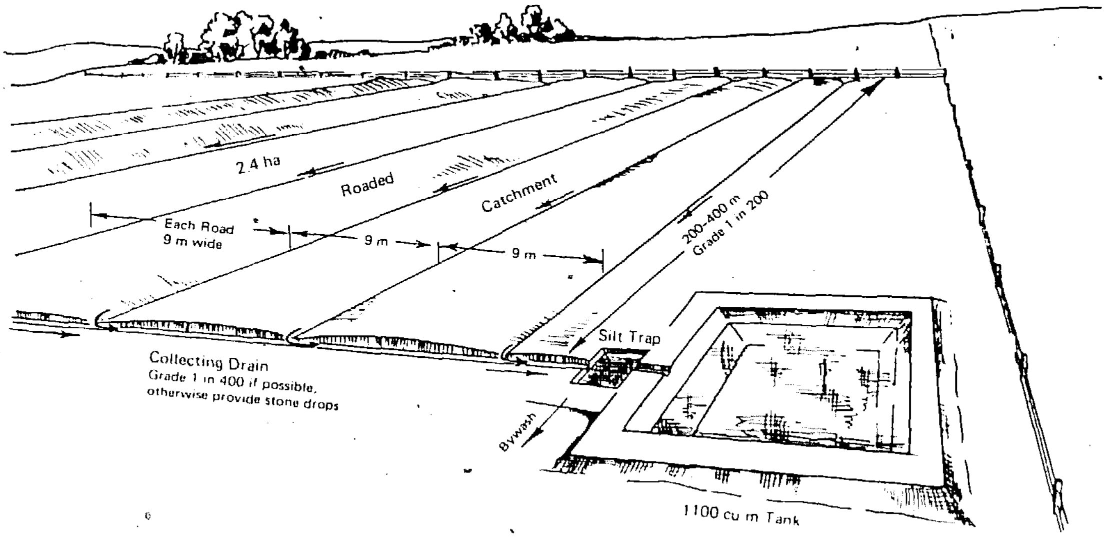

FIGURE 6 Western Australia rainwater-harvesting system. Catchments are graded and rolled and shed water with a minimum rainfall of 7.6 mm. They cost $30-$40 per acre (1968). They are designed so that for only 4.45 cm of runoff 1.6 ha of catchment will provide 800 cubic m of water. Catchments are cambered so that rainfall runoff quickly goes to the side of the "road," where a ditch conveys it to the main-collector drain and thence through a silt trap to the storage tank. (Taken from Department of Agriculture of Western Australia, 1950. See Selected Readings.)

runoff from many clay-containing soils (chapter 8). Sodium salts are intriguing as soil sealants because of their low cost, ready availability, and retardation of weed growth (FIGURE 24, page 33).

Other commonly tried water-repellent chemicals are silicones, latexes, asphalt, and wax (chapter 9). Although much more research remains to be done, these sealants now appear feasible for use on stable soils that do not swell with moisture.

Asphalt offers promise for building low-cost, impermeable catchments, particularly because it can be easily applied by spraying. In the United States hillslope catchments have been cleared of vegetation, smoothed, treated with a soil sterilant and two coats of asphalt to make rainwater catchments. One coat seals the pores; the other protects against weathering. Asphalt catchments on suitable slopes have been found to last 4 or 5 years. Problems caused by unstable soil conditions, oxidation, and penetration by germinating plants have recently been overcome by reinforcing the asphalt with plastic or fiberglass and covering the catchment with gravel.

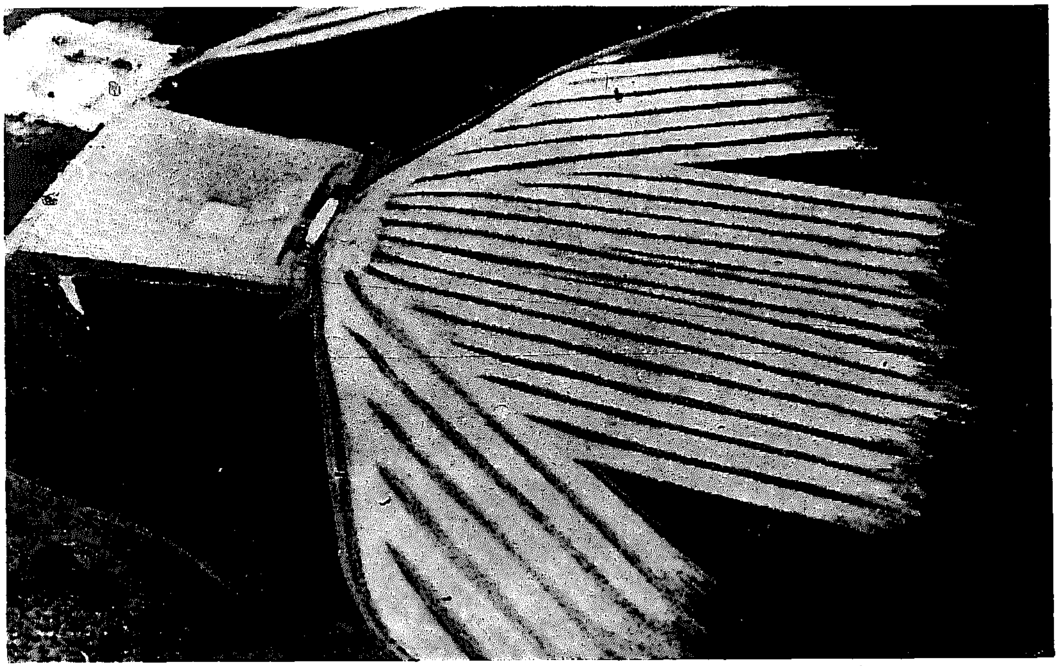

FIGURE 7 A modern rainwater-harvesting catchment south of the Stirling Range in Western Australia. The average annual rainfall in this area is 500 mm, falling during seven winter months. Natural ground surface is sandy with a clay subsoil. The sand is moved into rows; the clay exposed by the roading process is shaped and spread to cover the whole surface. The ridges discharge runoff water into a channel which conducts it to the square tank (capacity 3000 m^3). Main advantages are that the system uses the existing soil and can be built with readily available equipment. Smoothing and compacting the steep "road" surfaces is most important, here achieved by tractor and rubber-tired roller. The system appears suitable for many other arid and semiarid areas. (D. J. Carder and M. Hollick)

Paraffin wax has recently been used as a soil-sealant (FIGURE 8). Granulated wax spread on the ground melts in the sun and flows into the pores to produce a surface that readily sheds water. The wax can also be melted and sprayed on the ground. In tests,[3] wax-treated plots yielded an average of 90 percent of the rainfall as runoff, compared to 30 percent from untreated plots. Runoff water from the wax plots had low salt content (less than 50 mg per l) and almost undetectable organic matter.

Soil Covers

Instead of making the soil itself the water-shedding surface, it may be better in some situations to cover it with a waterproof cover. On porous or unstable soils in particular, maintaining other methods would be too costly.

Plastic sheet, butyl rubber, and metal foil offer opportunities for building low-cost rainfall catchments, but they are easily damaged by wind. Plastic films covered with gravel (FIGURE 9) have proved more successful; the gravel protects the underlying membrane against radiation and wind damage. These catchments, if properly constructed and maintained, can be durable, with a projected life of more than 20 years. They are useful where gravel is readily available and maximum runoff is not required (gravel retains some of the water).

General Principles

Water-harvesting methods are site specific. Before a system is installed, one must know:

- the soil (especially characteristics of water-holding, runoff, and erodability);
- the topography (slope and the direction followed by natural runoff);
- the precipitation characteristics (amount, reliability, etc.); and
- the climate (wind, sunlight, temperature, etc.).

Because rainfall in arid lands is intermittent, storage must usually be an integral part of any rainwater-harvesting system. However, when water-harvesting techniques are used for runoff farming (chapter 2), the water is "stored" in the cultivated soil itself. Sometimes it is possible to build catchments to feed existing—even ancient—water-storage structures (FIGURE 2).

Advantages

Surprisingly, the livestock-carrying capacity of many arid rangelands is limited more by a lack of drinking water than by a lack of feed. Rainwater

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[3] Fink, et al. 1973. (See Selected Readings.)

FIGURE 8 Paraffin wax is shredded and spread for rainwater harvesting in Arizona, USA. Melted by the sun, the wax flows into and seals soil pores, making a water-repellent surface that sheds water efficiently. (U.S. Department of Agriculture)

FIGURE 9 Laying polyethylene sheet for a rainwater-catchment in the Sonoran Desert, Arizona, USA. Sheet was later covered with gravel for protection against damage and sunlight. (C.B. Cluff)

harvesting may be the only source of extra water. Improving drinking-water supplies on arid rangelands or other remote watershed areas increases the value of these grazing lands and allows the available feed to be used more fully.

A water-harvesting system, once installed, will provide water without requiring fuel or power.

Recently, catchment construction costs have fallen sharply, and further cost reductions seem possible. The more promising chemical treatments and soil covers (such as wax, reinforced-asphalt membranes, and gravelled plastic) provide sediment-free, high-quality water for less than U.S.$0.05 per m^3 in a 300-mm rainfall zone in the southwestern United States.[4] Under favorable conditions the land alteration methods are the least expensive of all and could provide water suitable for most agricultural purposes at much lower cost.

Arid developing countries that produce and refine crude oil could use asphalt to construct water-harvesting catchments. Heavy petroleum fractions such as asphalt have limited demand and are often persistent pollutants, difficult to dispose of.

[4] Cluff, et al. 1972. (See Selected Readings.)

Limitations

Because rainwater harvesting depends on natural rainfall, it is no more reliable than the weather. Without adequate storage, the system will fail in drought years. In locations with an average annual rainfall of less than 50 to 80 mm, rainwater harvesting will probably never be economically feasible.

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

Today, little expertise is available for designing rainwater-harvesting systems. Furthermore, in many arid areas data are lacking on rainfall intensity and variability.

A rainwater-harvesting catchment must withstand weathering and occasional foot traffic. Fencing may sometimes be required. Environmental contamination must be constantly considered. Colored or contaminated runoff water will require treatment before it can be used for human consumption. (A simple system that uses a sand filter is shown in FIGURES 10 and 11.)

Most soil treatments (especially the cheaper ones) have a limited lifetime and must be renewed periodically. They also require occasional maintenance because of cracking caused by unstable soils, oxidation, and plants growing up through the ground cover or treated soil. No one material has proved superior for all catchment sites.

Stage of Development

Rainfall harvesting is almost 4,000 years old: it began in the Bronze Age, when desert dwellers smoothed hillsides to increase rainwater runoff and built ditches to collect the water and convey it to lower lying fields (FIGURES 2 – 4). This practice permitted agricultural civilizations to develop in regions with an average rainfall of about 100 mm, an inadequate rainfall for conventional modern agriculture.

In modern times, but before 1950, only a few artificial catchments were built, mainly by government agencies to collect water for livestock and wildlife on islands with high rainfall and porous soils (the Caribbean island of Antigua, for example[5]). The cost was usually high. In the 1950s interest in

[5] Bateman, 1971. p. 11 (See p. 5.)

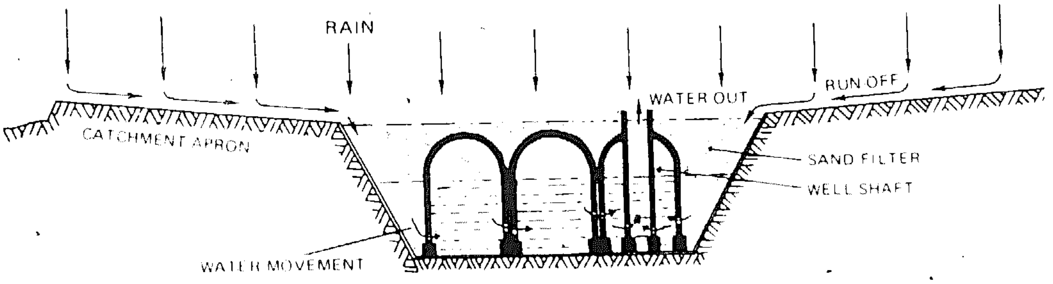

FIGURE 10 An experimental rainwater catchment with a sand-filled water-storage tank. The sand reduces evaporation and filters the water as it enters and is withdrawn, making water suitable for drinking. Tank is lined with thin plastic; storage capacity is increased by constructing beehive-shaped cells out of stacks of plastic sausages, described in FIGURE 12. (Intermediate Technology Development Group)

rainwater harvesting increased, and some lower cost treatments were installed. One of the most extensive is in Western Australia, where several thousand hectares of shaped, compacted earth catchments supply water for both households and livestock.[6] (See FIGURES 6 and 7.) Their performance is good when they are properly maintained. Approximately 240 ha of asphalt or asphaltic-concrete catchments have also been constructed to furnish water for 32 small towns in Western Australia.[7]

Currently, rainwater harvesting is for small-scale use, for farms, villages, and livestock. The land-alteration method is ready for immediate worldwide use. Australia and Israel use it already; in the Sudan and Botswana (FIGURE 12) catchment tanks have been introduced in technical assistance programs.

Chemical treatments and ground covers, though still mainly experimental, are used on a worldwide, but slight, scale. Proved to be technically feasible and successful, they are not yet economically attractive enough to generate widespread adoption.

Needed Research and Development

No method of rainwater harvesting has been subjected to a long-term economic analysis. Large field trials in different areas are needed to build up a data base that could lead to a better understanding of the economic viability of different methods in different economic environments. Developing countries particularly need the data, because most of the technology was designed for Israel, Australia, or the United States. With adaptive research to fit the needs, economics, and materials of developing countries, rainwater-harvesting methods may be of exceptional and immediate value.

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[6] Carder. 1970. (See Selected Readings.)
[7] Kellsall. 1962. (See Selected Readings.)

FIGURE 11 Capping 2-m-tall internal water-storage cells with soil-cement-filled sausages (FIGURE 12). The area will next be back-filled with sand. This technology requires only a spade, funnel, carving knife, and mallet. Kordofan Province, Sudan. (M. G. Ionides)

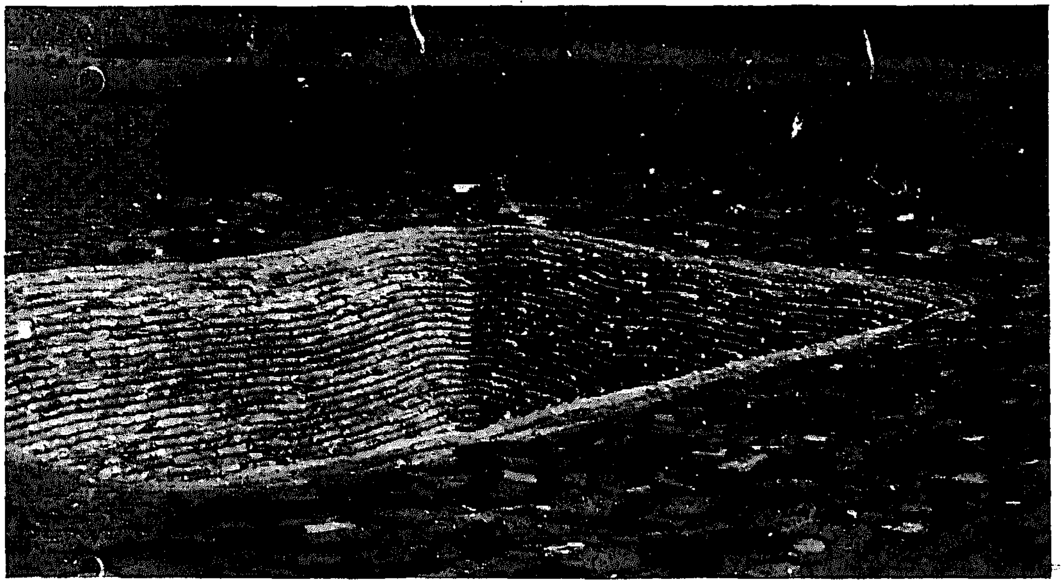

FIGURE 12 Catchment tank at Palapye Central School, Botswana, paved with mud and flat stones and sealed with a plastic liner. Revetment is made of "sausages"–thin-plastic tubes filled with soil-cement. Tubes are sealed at one end, and soil containing a small amount of cement is poured in. Tubes are then pricked with nails and placed in a shallow pan of water. Before the cement sets the tubes are stacked in place. No formwork is needed; the soil-cement is self-curing. (See also chapter 9.) The sausages are a modern, cheap, do-it-yourself technology. Water-storage tanks or cisterns with a catchment alongside to run the rainfall in are ancient devices, often forgotten today. (Intermediate Technology Development Group)

The major technical-research need is to reduce the costs of sealing catchment soils and to make the treatment practical for a wider variety of soils and situations. Industry is continually formulating new materials which should be continually monitored and evaluated for use in rainwater harvesting.

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Contacts

(See also Contacts, chapter 2.)

Animal Husbandry Farms, University of Sydney, Camden, New South Wales, 2570, Australia (H. J. Geddes)

Botany Department, Hebrew University of Jerusalem, Jerusalem, Israel (M. Evenari, L. Shanan)

Departamento de Suelos e Ingenieria Agronoma, Instituto Tecnologico de Estudios Superiores, Monterrey, Mexico

Department of Soil and Water Science, Faculty of Agriculture, Hebrew University of Jerusalem, Rehovoth, Israel (D. Hillel)

District Soil Conservationist, Western Soil Conservation District, Soil Conservation Service of New South Wales, P.O. Box 118, Condobolin, N.S.W. 2877 , Australia

Doxiadis Ionides Associates of London, Ockham Mill, Ripley, Surrey, U. K.

Hydraulic Engineers Branch, State Public Works Department, Perth, Western Australia

Irrigation and Water Supply Commission, P.O. Box 74, North Quay, Brisbane, Queensland 4000, Australia (A. M. Carmichael)

Ministry of Agriculture, Khartoum, Sudan

Northam District Office, Department of Agriculture of Western Australia, Northam, Western Australia (D. J. Carder)

Soils Division, Department of Agriculture of Western Australia, Jarrah Road, South Perth 6151, Australia (I. A. F. Laing)

Soil Conservation Service of New South Wales, Flotta Lauro Building, 18-24 Pitt Street, Sydney, N.S.W. 2001, Australia (J. C. Newman)

University of Western Australia, Department of Civil Engineering, Nedlands, Western Australia (M. Hollick)

U.S. Department of Agriculture, Agricultural Research Service, Berkeley, California 94705, USA (L. E. . Myers)

U.S. Water Conservation Laboratory, Phoenix, Arizona 85040, USA (K. Cooley, G. Frasier)

Water Resources Research Center, University of Arizona, Tucson, Arizona 85721, USA (C. B. Cluff)

2 Runoff Agriculture

Once rainwater runoff has been harvested from slopes (see chapter 1), it can be used for crop production (FIGURES 13 and 14). The combination is known as runoff agriculture. FIGURES 15-24 show ingenious, simple runoff agriculture systems in various parts of the world.

Runoff agriculture was developed almost 4,000 years ago to permit crop production on lands receiving as little as 100 mm average annual rainfall. Extensive investigations reveal that ancient farmers in the Middle East cleared hillsides to increase runoff water and built rock walls along the contours to collect it and ditches to convey it to lower lying fields (FIGURES 2-4). These systems allowed agricultural civilizations to survive in desert regions that today support only a small human population and produce few crops. Warfare and political upheavals resulted in mismanagement and neglect of the ancient farms, but the techniques of runoff agriculture are still applicable today. Runoff farms, using modern technology and crop varieties selected for local conditions (chapter 14), could benefit many desert regions. Artichokes, asparagus, flower bulbs, some fruits and nuts, barley, sorghum, pearl millet, and forages all are potentially important crops for runoff agriculture; most are now grown in large runoff-agriculture field trials in the Negev Desert.

Methods

In runoff agriculture the principles and practices depend on rainwater harvesting (described in chapter 1). The basic need is a rainwater catchment that provides enough water to mature the crop. Obviously, the crop's own water requirements (chapter 14) and general water conservation techniques (chapters 7-16) are crucial to a successful harvest. Poor crop yields in drought years are usually offset by production in good years.

The type of farming practiced must make the best use of the water. In general, perennial crops with deep root systems adapt better to runoff agriculture, because they can use runoff water stored deep in the soil, safe

FIGURE 13 A good barley crop produced by runoff agriculture in the Negev Desert. (L. Evenari)

from evaporation. Some deep-rooted, drought-resistant fruit trees can be very successful. Shorter lived crops can also be grown; grains, such as pearl millet, that mature rapidly and require only one rainfall hold particular promise.[8] Plants that become dormant during dry periods and begin growing when water becomes available are particularly suited to runoff agriculture.

The desert soils and climate of the Negev have been found suitable for a variety of crops under runoff agriculture. Excellent yields have been obtained from pasture plants, field crops, and orchards, well above those of dryland farming and comparable to yields in irrigated farming (TABLE 1).

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[8] A companion report on tropical plants, now in preparation, describes some lesser known grains that can be grown to maturity with a single flood irrigation. (See BOSTID publication 16, p. 153.)

FIGURE 15 Reconstructed ancient farm at Avdat in the Negev. Farm is, and was, watered by runoff from surrounding slopes and wadis. In the foreground are four reconstructed terraces; in the background, four reconstructed channels lead runoff to the farm. To the right are traces of three channels that once carried runoff water to the lower terraces. Ratio of catchment to cultivated area is 20:1–each ha of cultivated land receives runoff from 20 ha of slopes, as well as direct rainfall. Cultivated area receives water roughly equal to a rainfall of 300-500 mm from actual rainfall of 100 mm. (L. Evenari)

be collected in easily constructed channels on the hillsides and were small enough to prevent uncontrollable amounts of water (FIGURE 1). Channels directed the water to cultivated fields which were terraced and had stone spillways so that surplus water in one field could be led to lower ones. Farmers dammed the small channels between the catchment and the fields with rocks; by removing strategic rocks from the channel walls they could guide the water to different fields at will.

A form of runoff farming that utilizes water from small, deliberately built catchments has been practiced in Botswana.[9] The water is used on school vegetable gardens. The catchments have included school playgrounds, roads, etc. (FIGURE 12).

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[9] Intermediate Technology Development Group, Ltd. 1969. p. 70 (See p. 21.)

FIGURE 16 Orchard in Negev. Rainwater falls on the slope behind and runs down to strategically located ditches that convey it to the trees. In temperate regions agriculture is based on direct precipitation and on practices, such as plowing, that encourage rain to infiltrate the soil. Runoff agriculture is an indirect method suited to arid lands; it collects rain from a larger area and concentrates it on a smaller, cultivated area. (L. Evenari)

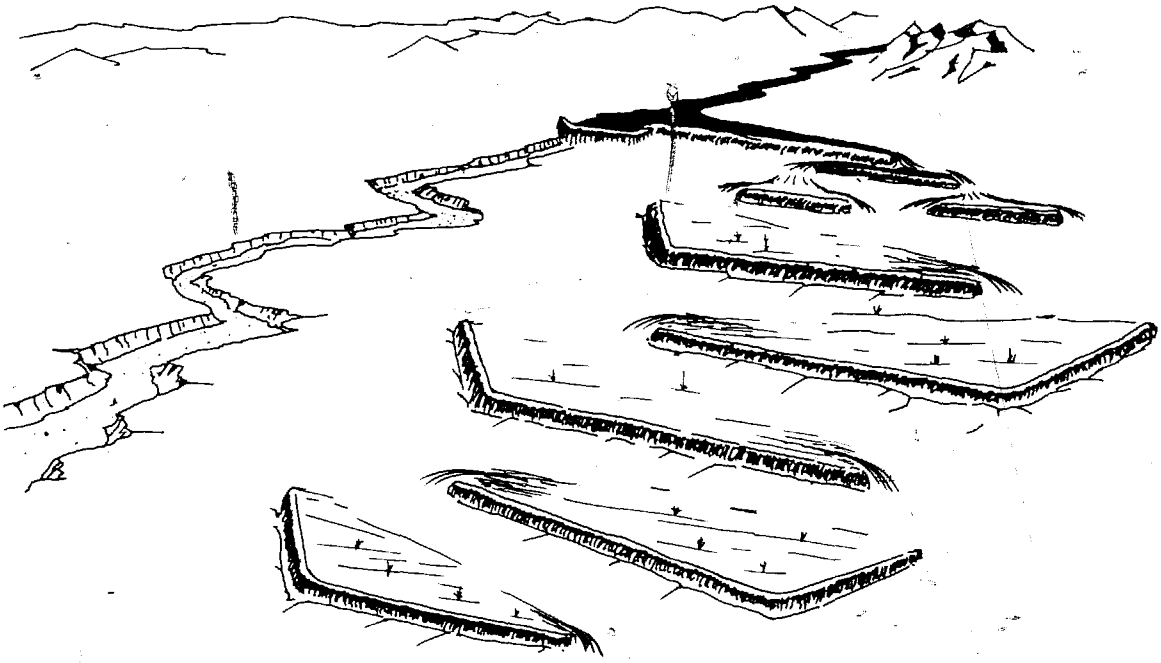

FIGURE 17 Sketch of water-spreading dikes built in Pakistan. Zigzag pattern slows the torrent of floodwater and allows it to penetrate the soil. Crops are then planted in the wetted areas behind the dikes. (Adapted from French and Hussain. 1964. See Selected Readings)

Water-Spreading

In arid areas the limited rainfall usually falls during short, intense storms. The water swiftly drains away into gullies, and then flows, sometimes for many miles, toward the sea or an inland lake. Water is lost to the region, and floods caused by this sudden runoff can be devastating, often to areas otherwise untouched by the storm.

Water-spreading is a simple irrigation method for use in such situations: floodwaters are deliberately diverted from their natural courses and spread over adjacent floodplains (FIGURE 17) or detained on valley floors (FIGURES 18 and 19). The water is diverted or retarded by ditches, dikes, small dams, or brush fences. The wet floodplains or valley floors can then be used to grow crops. Water-spreading is also frequently practiced on range and pasture lands.

Water-spreading systems need a careful design and engineering layout to withstand floodwaters. Potential sites are found on many arid and semiarid ranges, sometimes (as in the rainshadow of a mountain range) where floods are more common than rain. They must be selected with full consideration for topography, soil type, and vegetation. Two requirements are essential:

- Runoff waters, available for spreading, produced by an upstream drainage area that gives at least a few water flows each year; and

FIGURE 18 Man-made terraces (reinforced by unpalatable bushes) built in ancient times to slow down and capture floodwaters in this wadi in the Negev. Built thousands of years ago, some are still used for farming by Bedouins. Terrace walls are 10-50 m apart and about 30 cm high. Rain brings wild flooding; surplus water pours over the terraces; but the walls retain a pool of water that slowly sinks into the soil. Experiments here have shown that these walls are high enough to fully moisten enough soil to get crops such as barley or wheat to maturity. Water spreading may predate irrigation. Ancient farmers built many such systems throughout the Middle East, South Arabia, and North Africa. (L. Evenari)

- Floodplains or gently sloping areas where the soils are suitable for crop production.

Inherently more risky than standard irrigation, the system depends on fairly regular rainfall and on soils (e.g., loess) that facilitate runoff. A constant concern is that sediment and gravel carried by floodwaters may adversely affect the crop land.

Microcatchment Farming

A plant can grow in a region with too little rainfall for its survival if a rainwater-catchment basin is built around it, forcing rainfall from a larger than normal area to irrigate the plant. This practice is called microcatchment farming. The previously described principles apply to this microscale runoff agriculture; many of the same soil treatments mentioned in chapter 1 can be used.

FIGURE 19 In 1972 near the small town of Tchirozerine (close to Agades), Niger, West Africa, Touareg nomads build a rock wall to capture flood waters. The soils here absorb little moisture, and the rainfall runs away in flash floods. Using stones gathered from the fields, Touareg workers built eight 1-m-high walls across the plains so that rain is retained, and absorbed by the soil. When summer showers fell in 1973, the water retained by stone dams and walls flooded nearly 1 square mile on the plain and grass flourished–extraordinary events in that area. (Oxfam-America)

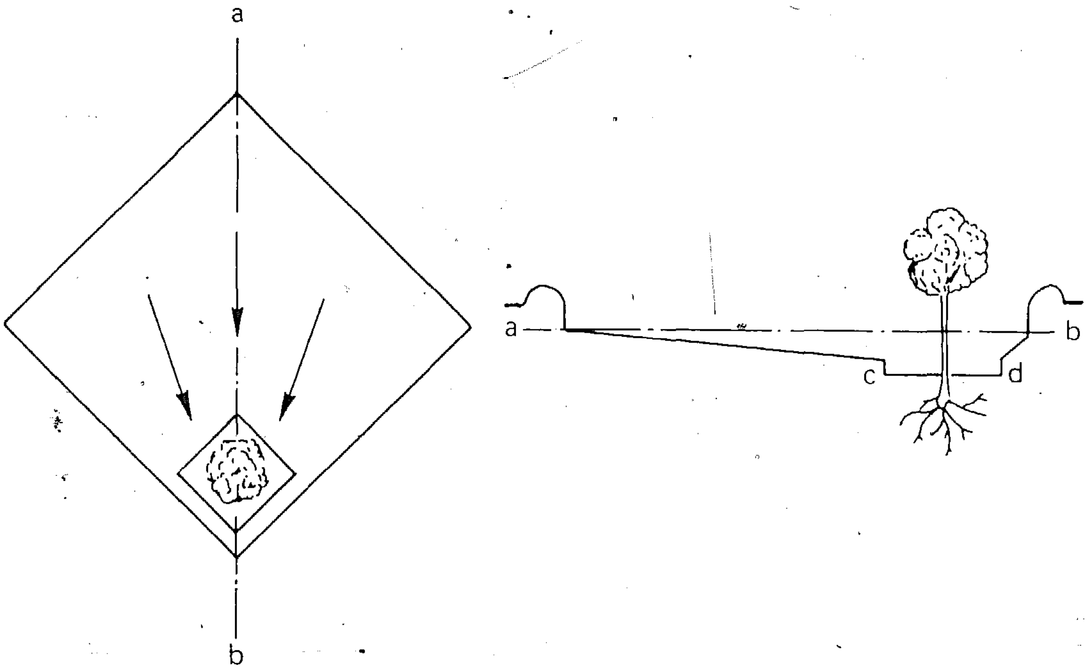

FIGURE 20 Plan and cross-section of a microcatchment. Arrows indicate direction of runoff flow. Cultivated plot (c–d) is placed at the lowest point of the natural terrain within the catchment; its position varies. Walls are 15-20 cm high; c–d is about 40 cm below the catchment, holding seeping water close to the plant; root-zone soil must be at least 1.5 m deep; the a–b distance can be less than 5 m or more than 30 m, depending on climate and crop. (M. Evenari)

Microcatchments used in the Negev Desert range from 16 m^2 to 1,000 m^2. Each is surrounded by a dirt wall 15–20 cm high (FIGURES 20–23). At the lowest point within each microcatchment a basin is dug about 40 cm deep and a tree planted in it. The basin stores the runoff from the microcatchment. The size of the basin is matched to the water harvest expected.

The basins are fertilized with manure, and, unlike the catchment area, their soil surface is kept loose to encourage water penetration. A mulch may also be used to decrease water evaporation from the soil (see chapter 9).

On an otherwise barren desert plain microcatchments provide enough additional water to ensure the growth of fruit trees and forage plants. Microcatchments and variations of this method are used in Tunisia for growing olives—and apparently have been since ancient times.

In the Negev microcatchment construction costs are very low—from US$5 to US$20 per ha, depending on the catchment size. The cash return from crops repays their construction costs within a few years.[10]

Microcatchments are more efficient than large-scale water-harvesting schemes (chapter 1) because conveyance losses are minimized. In light rains,

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[10] Evenari, Shanan, and Tadmor. 1971. (See p. 21.)

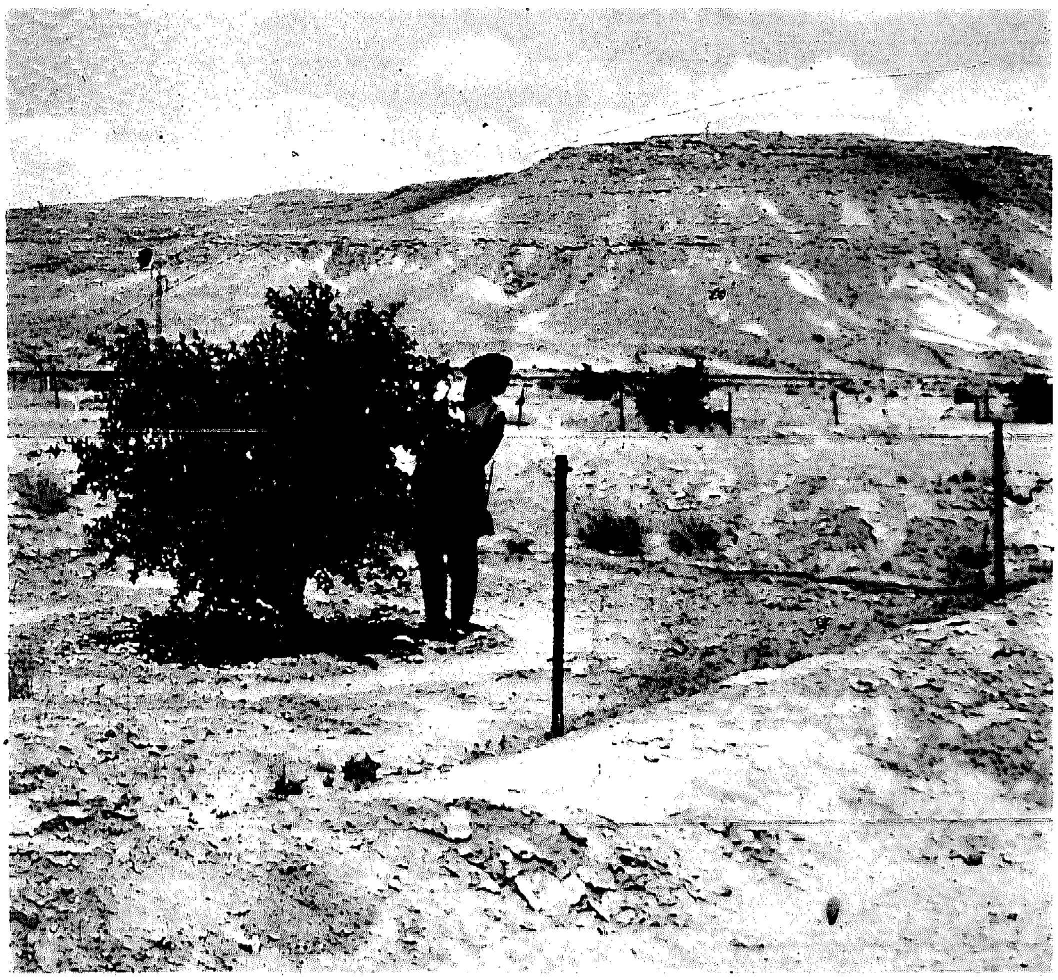

FIGURE 21 Microcatchment farming in the Negev. Pomegranate trees grow in 500-m^2 microcatchments in a 100-m-rainfall region. The only soil treatment is shaping. The orchard is less dense than those in temperate climates; 40-60 pomegranate trees per ha are planted. Smaller trees, such as grapevines, can use smaller catchments (80-100 per ha); catchments of just over 30 m^2 (320 per ha) are enough to grow a saltbush plant and guarantee a supply of forage even in severe drought. (L. Evenari)

they provide runoff water when others will not. It is much cheaper to convert a certain area into microcatchments than to construct a runoff farm because microcatchments do not need channels, conduits, terraces, and terrace walls. Also, microcatchments can be built on almost any slope, including almost-level plains, enabling the farmer to use large, flat areas unsuited for runoff farms.

Desert Strip (or Contour Catchment) Farming

Desert strip, or contour catchment, farming is a modification of microcatchment farming. It employs a series of terraces that shed water onto a neighboring strip of productive soil. They are often tiered up a hillslope

(FIGURE 24), but on level terrain an artificial slope for the catchment can be made by mounding soil between the strips.

The catchment section can be left in a natural state or cleared of rocks and vegetation, planted with range grasses, or made impervious by the sealants described in chapter 4. Desert strips are, in general, even easier to install and maintain than microcatchments. These methods are being tested in Arizona; in Wadi Mashash, Israel, it is used to produce grazing for sheep (FIGURE 14).

Advantages

Runoff water can allow plants to grow in otherwise too arid habitats. Highway edges often illustrate the principle: because the road acts as a catchment, roadside vegetation on the lower side is greener and more dense. It has even been proposed that water-storage tanks be built beside road pavement at the foot of suitable hillslopes to collect water.

Runoff agriculture can be used to make new agricultural lands where water is otherwise inadequate to support agriculture. And yields from already cultivated areas can be increased without installing costly irrigation projects to bring in water from a neighboring region. It has particular promise for marginal areas; runoff agriculture can lower the risk of crop failure.

Runoff used to grow forage can relieve grazing pressures on nearby rangelands. Overgrazed areas can be revegetated and the carrying capacity of grazing land greatly increased. For example, the weighted average productivity of an 80-ha water-spread area at "Conneybar," Byrock, New South

FIGURE 22 Microcatchments in Botswana with 2-year-old apricot trees. (U. Nessler)

FIGURE 23 Participants in the international training course in the Negev Desert preparing microcatchment plots (see chapter 2 Contacts). (U. Nessler)

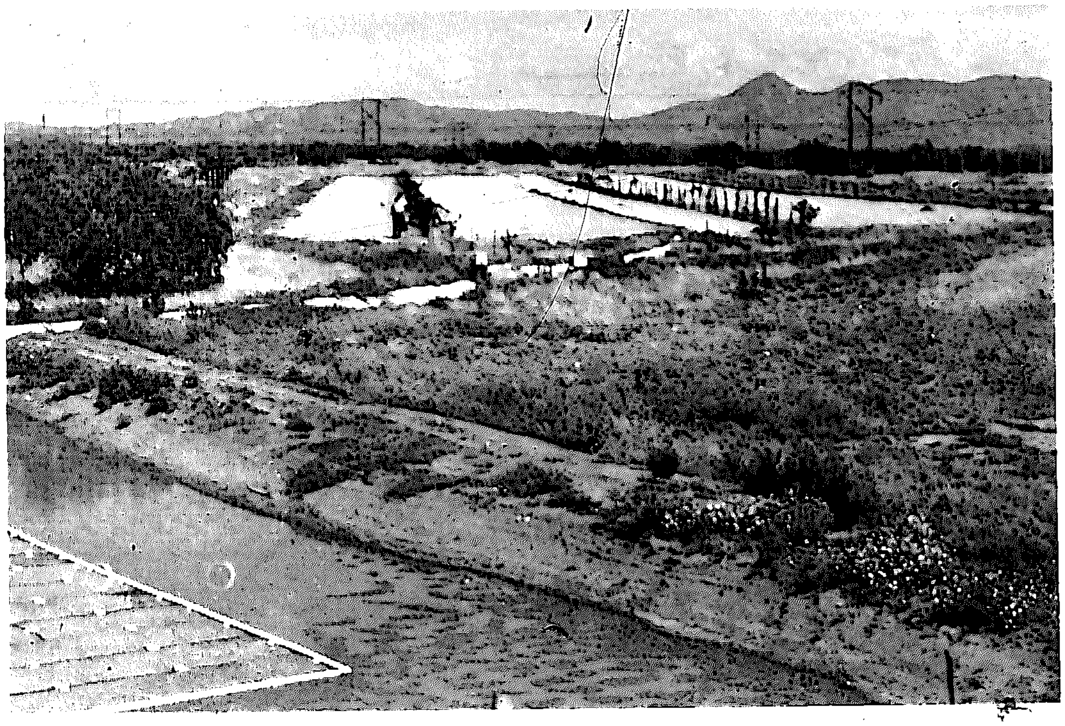

FIGURE 24 Desert strip runoff farming at Page Experimental Ranch near Tucson, Arizona, USA. Grapes are cultivated in drainage ways. Catchment area treated with sodium chloride remains bare; untreated foreground area has returned to native grasses. Bottom left-hand corner shows part of an expanded-polystyrene floating cover designed to reduce evaporation from the pond (see chapter 7). (C. B. Cluff)

Wales, Australia, from 1968 to 1973 was 2.66 sheep per ha. Without water-spreading the carrying capacity of this region is 0.18 sheep per ha (as measured over the 25 years, 1947–1972). Seasonal feed shortages still occur in poor rainfall years at Conneybar, but their consequences are much less than they would have been without water-spreading. High grazing intensities have been applied for short periods. Up to 586 sheep per ha have been grazed on a 28 ha pasture for periods of up to 4 days. Runoff-irrigated fields are used as special fields to increase control over, and minimize losses of, newly born animals and to hold stock during shearing, dipping, mating, etc.[11]

Runoff agriculture can extend the season during which forage is succulent and nourishing, providing green forage when it is especially needed.

Water-spreading can provide erosion control, for it deflects the torrent of water and dissipates its energy.

Limitations

Runoff agriculture requires a deep soil that can store water between rains. It works best for deep-rooted crops, such as trees and shrubs, which can tap stored water and depend less on frequent rainfall. Annual crops, in contrast, need rain at the beginning of the growing season and sometimes at intervals thereafter.

The method is enhanced by plant varieties able to withstand intermittently wet and dry soil. As in normal agriculture, yields also depend on insect and disease control.

Environmental prerequisites are

- A minimum mean precipitation of 80 mm per rainy season if the rainy season coincides with the cold period of the year, more than 80 mm if it occurs during summer when evaporation is greater;
- Crust-forming or impermeable soils on the catchment areas;
- Soils in the cultivated areas with high water-storing capacity;
- Not more than 2–3 percent salinity in the cultivated soil; and
- A minimum of 1.5–2 m of soil depth in the cultivated area (unless water-storage facilities are available).

In runoff agriculture the water must be distributed evenly over the cultivated area to prevent prolonged ponding, overirrigation, or deep percolation losses. In some cases the area to be cultivated can be constructed so that any excess spills to a lower collection level. The cultivated area must be uniform, without gullies or ridges. Before deciding on runoff agriculture, one needs to consider

- The water-use characteristics of plants to be grown;

[11] Cunningham. 1973. (See Selected Readings.)

- Their yields;
- Their ability to resist drought;
- Whether the soils in the cultivated areas can store enough water to mature the crop; and
- The amount of evaporation from the soil surface.

Stage of Development

In ancient times runoff agriculture was widespread over the whole arid region of the Middle East, southern Arabia, and North Africa. On many thousands of hectares of the Negev Desert, it was the basis for civilization (FIGURE 4).

Runoff agriculture has been shown to be technically sound for modern use, too. Its rebirth as a systematic method took place in the Negev Desert in Israel, where large-scale experiments have been conducted for the past 15 years (FIGURES 15, 16, and 21) and a training school for developing-country personnel is located at Wadi Mashash (FIGURE 23). Some microcatchment farming occurs today in several other arid countries such as Mexico, Botswana (FIGURE 22), India, Pakistan, and Australia. The microcatchment method is used to grow wheat and fruit trees over a 70,000-ha area in Khost province, Afghanistan.

Needed Research and Development

Runoff agriculture can be used today if care is taken in selecting the site, designing the system, and selecting the crop. With good management it can make arid wasteland productive and can be an economically sound investment. Modern experience, however, is limited to a few isolated projects. Intensive technoeconomic evaluations in several regions of the world with different climates, soils, and crops are needed to identify its potential for the future.

To make runoff agriculture more effective, there is a need to develop crops better suited to it (further discussed in chapter 10). For example, if crops matured in 60 instead of 80 days, the soil would not have to store so much water, the risk of crop failure would be lessened, the system would require less rainfall, and management requirements would be reduced.

In microcatchment farming the crucial problem is still the optimal size of the microcatchment for each species. It is obvious that this parameter is relative not only to each species but also to precipitation, soil quality, and steepness of gradient. We have much to learn about such matters. Other problems concern optimal depth and the size of the basin in relation to the size of the catchment area. These factors are most important because they determine, inter alia, the size of the surface area wetted by the flood and the volume and depth of the water column in the soil. These in turn affect the time during which the soil containing the root system is waterlogged and soil and root aeration is bad. A knowledge of these factors may even lead to different patterns of constructing the basins and the placing of the trees—perhaps on a knoll inside of the basin. There may also be the possibility of increasing runoff volume by pretreating the soil surface of the microcatchments in different ways.[12]

Technoeconomic studies are particularly needed for runoff agriculture using chemically treated and ground-covered catchments.

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(See also Selected Readings, chapter 1.)

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Central Arid Zone Research Institute, Jodhpur, India (H. S. Mann, Director)

College of Agriculture, University of Arizona, Tucson, Arizona 85721, USA (W. G. Matlock)

Department of Agronomy and Plant Genetics, University of Arizona, Tucson, Arizona 85721, USA (N. F. Oebker)

German Agricultural Group, P.O. Box 183, Kabul, Afghanistan

Intermediate Technology Development Group, Ltd., Parnell House, 25 Wilton Road, London SW1V 1JS, England

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3 Irrigation with Saline Water

Beneath many of the world's deserts are reserves of saline water, and many surface waters—estuaries, coastal lagoons, land-locked lakes, and irrigation return flows—contain fairly large amounts of salt. If saline water could be used for irrigation, more desert land could be cultivated; the nonsaline water now used in agriculture could be released for human consumption, reducing the need for expensive desalination schemes now contemplated for supplying urban areas.

Today, new appreciation of plant physiology and soil science and new irrigation techniques are showing that with careful management, saline waters can be used to grow a variety of crops.

Method

The salt resistance of crops largely determines the suitability of saline irrigation waters. The salt tolerance of crops has now been studied intensively, and adequate information for selecting crops of suitable resistance to saline waters is becoming available. Although only a few crops such as cotton, barley, wheat, sugar beets, rye grass, Bermuda grass, and the wheat-grasses *Agropyron elongatum* and *A. desertorum* are known to be salt tolerant, they are important in developing countries because they form the basis of much agricultural production. Salt-tolerant trees include the date palm, olive, pomegranate, and pistachio.[13]

In general, irrigation waters whose total dissolved solids are below 600 milligrams per liter (mg/l) may be used on almost any crop. If leaching (discussed later) and drainage are adequate, water from 500 to 1,500 mg/l can be, and is, widely used on all but the most salt-sensitive crops. Water of 1,000 - 2,000 mg/l can be used for crops of moderate tolerance, especially if frequent irrigation is employed. Water of 3,000 - 5,000 mg/l will produce high yields only from highly tolerant crops, such as those listed earlier. Despite claims to the contrary, irrigation with undiluted seawater has not

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[13] Some lesser known salt-tolerant plants are described in a companion report on neglected tropical plants, now in preparation. (See publication 16, p. 153.)

proved practical for producing crops. Seawater has a total salt content of about 35,000 mg/l, greatly exceeding the tolerance of even the most salt-tolerant crop studied to date—Suwanee Bermuda grass *Cynodon dactylon*, which can tolerate about 12,000 mg/l.

The type, as well as concentration, of salt in the water is important. For example, the relative concentrations of sodium to calcium and magnesium affect a water's suitability because high sodium ratios affect soil structure (compare FIGURES 46 and 47) and plant nutrition. The anion of the salt, e.g. chloride or sulfate, may also be important.

In the practice of saline irrgation, the basic premise is that proper irrigation and drainage management prevent salts from building up in the soil. It is essential to avoid this buildup by leaching: applying more irrigation water than the plant requires so that the extra water carries the salts down

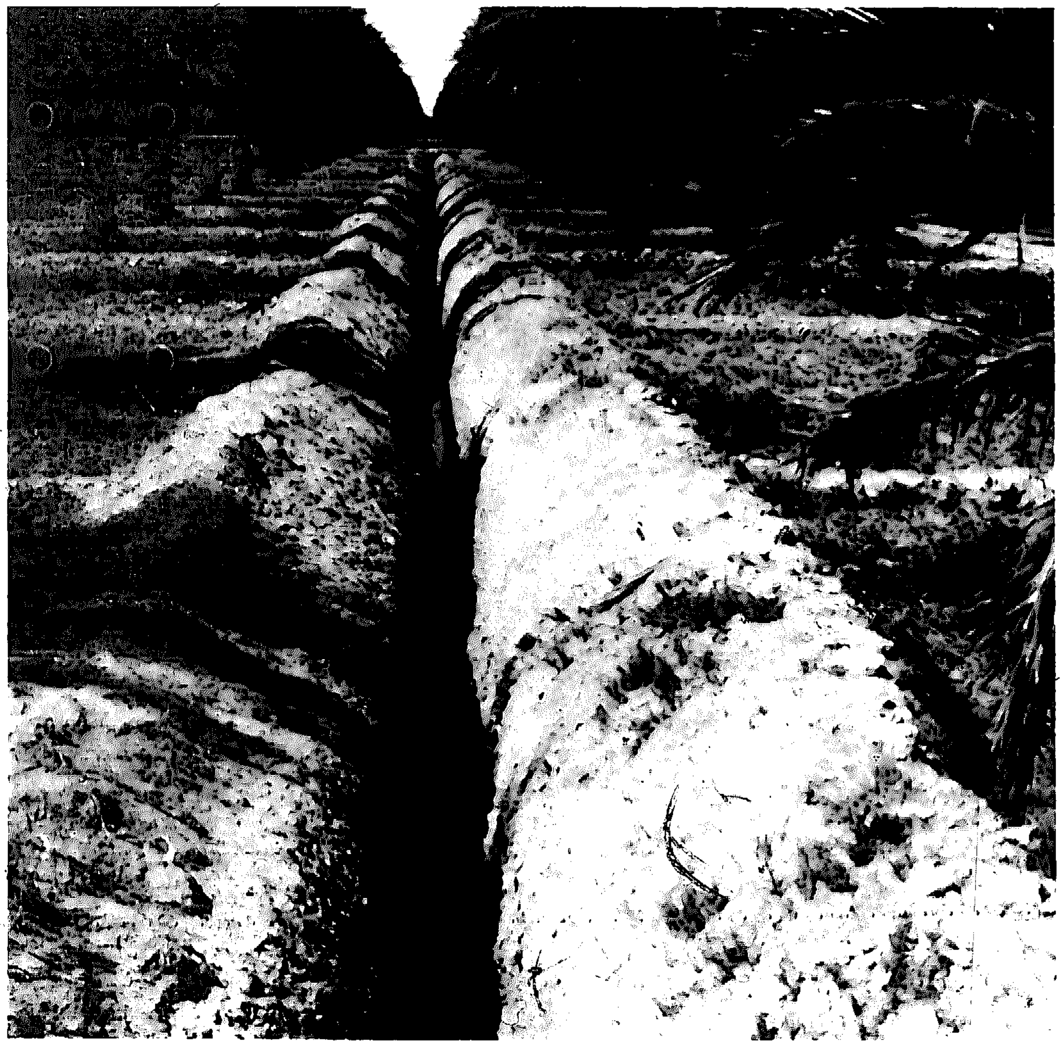

FIGURE 25 Date palms in Southern Tunisia that have been irrigated for 4 years with water containing 2,000 mg/l salts. The extensive drainage system is required to facilitiate leaching. (J. W. van Hoorn)

below the plant's roots. The suitability of saline water for irrigation is thus also governed by the leaching characteristics of the environment, i.e., whether they facilitate or retard the removal of salts from the root zone (FIGURE 25). If the leaching characteristics of the soil particles or the overall drainage of the area are insufficient, soil salinity will increase, and the final result may be a barren wasteland. Light-to-medium-textured soils that are not subject to structural changes that restrict water flow are more likely to be successfully irrigated with saline waters.

According to recent findings, new irrigation methods can increase a crop's tolerance to salinity. Compared to furrow irrigation, trickle irrigation (chapter 10), for example, has been shown to improve yields of crops irrigated with saline water (2,000 - 2,500 mg/l). The salt stresses on a plant are aggravated as the soil dries out and the salt concentration increases. Frequent irrigations (as in the trickle method) minimize such stresses.

Advantages

Saline ground, surface, and estuarine waters are widely available but not often used for irrigation; new research findings make it possible to use them more widely for agriculture, landscaping, etc.

The cost of using saline water, especially from aquifers near the surface, is not likely to be excessive. At Kibbutz Mashabei S'deh in the Negev Desert

FIGURE 26 Irrigating cotton with brackish water (2,500 ppm dissolved salts) caused a stunted plant, but the cotton yield was 59 percent higher than with freshwater irrigation. Spraying plants with the transpiration-suppressing plant hormone abscisic acid (see chapter 13) further increased cotton yield. (M. Twersky)

FIGURE 27 Maize and fodder sorghum in Tunisia irrigated with sweet water containing only 200 mg/l of salt (left side) and with saline water containing 3,500 mg/l (right side). Respective yields of maize 9,000 and 5,000 kg of grains per ha; of fodder sorghum (foreground) 90 and 50 tons of green matter per ha. (J. W. van Hoorn)

FIGURE 28 Rhodes Grass (*Chloris Gayana* Kunth) irrigated with 2,600 mg/l saline water. (Kibbutz Mashabei S'deh, Israel)

(100-mm rain) a 4,800 m^3/day electrodialysis plant desalts underground brackish water. For comparison, water from the same well (2,600 mg/1) has been used to irrigate cotton (FIGURE 26), wheat, maize, sorghum (FIGURE 27), Rhodes grass (FIGURE 28), Bermuda grass, etc., and various vegetables. After 3 years, economic and general-utility considerations favor direct use of the saline water over the electrodialysis; the saline aquifer is now used for this purpose.[14]

Limitations

Although saline-water irrigation holds exciting possibilities for the future, it does not promise the conversion of vast stretches of arid land into cultivated fields. Many crops cannot tolerate it; indiscriminate use may severely damage the soil; and suitable soil and climate do not always coincide with suitable water. Furthermore, the greater management skills necessary may not be available.

To irrigate with saline water and maintain good yields demand good water management by trained specialists. The type and mix of salts and their concentrations in the water need to be investigated before a decision is made to use saline waters. Saline-water irrigation will increase the salinity of groundwater and possibly make it unsuited for other uses. If groundwater is the source, the project may have a short useful life. If poorly managed, irrigation with saline water may seriously damage the soils and even make them barren.

When irrigation water contains 5,000 mg/1 or more of salts, the leaching requirements for even highly tolerant crops may be substantial. For example, more than 25 percent extra water may be needed just to move the salts below the root zone; if less is used, salination of the soil occurs because salts are not removed as fast as they are added.

Even highly tolerant crops may go through salt-sensitive stages when they need low-salt water. For example, seedlings of small grains and sugar beets are sensitive, though the adult plants are not; saline water may impair their development.

One must be careful in applying test results from temperate regions to tropical arid lands. The same crop grown in temperate or humid regions can tolerate more highly saline water than it can in arid regions because rains (and soil waters) dilute the irrigation water. Lower temperature may also increase a plant's salt resistance.

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[14] Information provided by J. Schecter, Acting Director, University of the Negev-Research and Development Authority.

Stage of Development

The use of highly saline water for irrigation has been fairly limited. As already mentioned, large-scale experiments are under way using brackish water for irrigation on sand and sandy loam soils in the Negev Desert. The use of brackish water for irrigation has been studied during 7 years of field research at six experimental stations in Tunisia. Major objectives of this UNESCO-sponsored program were to determine the optimum use of the available saline surface and ground waters and to control soil salinity through improved irrigation techniques. As a result, saline river water containing 2,000 - 3,500 mg/1 of salt is today used in Tunisia for irrigation on a large scale in the Medjedah Valley (and other locations) on medium-to-heavy-textured soils fitted with an extensive tile drainage system (FIGURES 25 and 27).

Needed Research and Development

Breeding and selection of plants that can use water of higher than normal mineral content is very much needed. The greatest success will undoubtedly be with crops already showing some tolerance to salinity, e.g., coastal Bermuda grass, barley, cotton, wheat, sugar beets, and perhaps the more salt-tolerant vegetables. Some varieties with greater salt tolerance than usual are known and may become the basis for breeding stock.

Using saline water for irrigation requires sophisticated management, but detailed management requirements are not fully understood and need careful investigation. The following need particular attention:

- Determining the relationship between saline water and the physiological stress performance of plants;
- Alleviation of stresses by different irrigation, fertilization, soil aeration, leaching practices, nutrients, hormones, chemical and physical treatments, etc.; and
- Field application of the knowledge gained.

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Central Soil Salinity Research Institute, Karnal, Punjab, India

Centre de Recherches pour l'Utilisation de l'Eau Salee en Irrigation, Route de Soukra, B. P. 10, Ariana, Tunisia

Agricultural University, De Nieuwlanden, Nieuwe Kanaal 11, Wageningen, The Netherlands (J. W. van Hoorn)

Kibbutz Revivim, Negev, Israel (J. de Malach)

Ministry of Agriculture and Natural Resources, Nicosia, Cyprus

Negev Institute for Arid Zone Research, Beer Sheva, Israel (J. Schecter)

U.S. Salinity Laboratory, U.S. Department of Agriculture, Agricultural Research Service, P.O. Box 672, Riverside, California 92502, USA (J. van Schilfgaarde, Director)

Water Resources and Development Service, Land and Water Development Division, Food and Agriculture Organization of the United Nations, Via delle Terme di Caracalla, 00100 Rome, Italy.

4 Reusing Water

Reusing water can greatly lower the overall demand for water resources. Wastewater can be used for irrigation, for industry, for recharge of groundwater; in special cases, properly treated wastewater has been used for municipal supply. With careful planning, various industrial and agricultural demands may be met by purified wastewater, thereby freeing freshwater for municipalities, which require better water, suitable for human consumption.

Water reuse may have greater impact on the future usable water supply in arid areas than any of the other technologies discussed in this report.

Methods

Agricultural Use

Spreading wastewater on marginal land to create new farmland may prove particularly important in arid countries. In such areas reclaimed water will probably be used first for irrigation. Filtering wastewater through soil removes all particulate matter: most cations and some anions (including phosphates) are strongly adsorbed, and organic matter is decomposed by soil bacteria. These actions can contribute plant nutrients to soil (FIGURES 29 and 30).

Using municipal wastewater for irrigation is especially attractive where agricultural lands are located close to cities, because the plant nutrients in sewage would otherwise go to waste. Some biological treatment of sewage should precede land application, but for many crops the degree of treatment required is so low that little technology and capital investment are required. (Mexico City uses vast amounts of untreated sewage as irrigation water.) Where irrigation systems are already in use, connecting them to municipal systems is fairly simple, though institutional arrangements may prove difficult. The American Public Works Association has recently stated that

> . . . on the basis of the exhaustive study which was undertaken, it must be concluded that the land application of wastewaters offers a viable alternative

FIGURES 29, 30 Two maize crops on a 10-ha plot at Rhodesia's Salisbury sewerage works, 1971-72 season. Tall maize on left was given a particularly heavy preirrigation with treated sewage. Stunted maize at right was irrigated almost entirely by rainfall. No additional fertilizer was added to either crop. The contrast shows very clearly the fertilizing effect of nutrients in the sewage. (Rhodesia Agricultural Journal)

to advanced treatment processes and deserves serious consideration by many communities and industries throughout the United States. Land needs, when taken in perspective with total land uses, are not unreasonable and may, in fact, play a desirable social role by providing green belts and open areas, and preserving rich farm lands and cloistered areas. The conclusions of the report point to the almost unqualified success of this method of application, both in this country and throughout the world, when the facility has been properly operated and efforts have been made to apply sound engineering, geological and farming expertise to design, construction and control procedures.[15]

Since 1892, Melbourne, Australia, with a present population of almost 2 million, has disposed of its wastewater in irrigation at the 109 km^2 Board of Works Farm at Werribee (FIGURE 31). A total of 4,200 ha of the farm is employed for irrigated pasture of which 1,370 ha are used for grazing 15,000 head of cattle through the year. Forty to fifty thousand sheep are fattened during spring and summer. Health restrictions are imposed only on the sale of

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[15] American Public Works Association. p. viii. (See Selected Readings.)

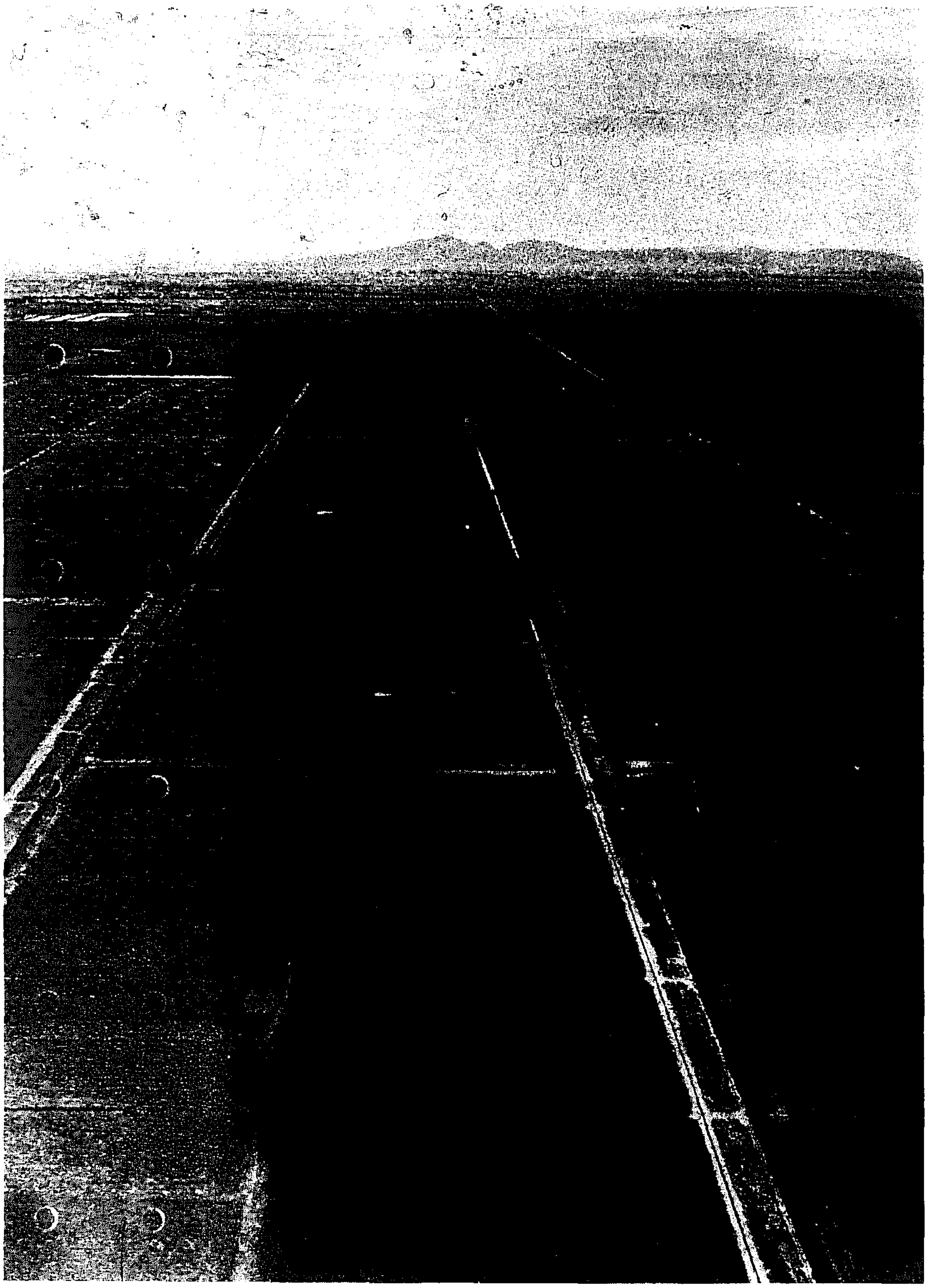

FIGURE 31 This Melbourne and Metropolitan Board of Works Sewerage Farm at Werribee, Australia, has long used treated sewage from the city of Melbourne as irrigation water. This formerly barren, arid, windswept plain is the major sewage-disposal facility, serving more than 1.5 million people. (Sewage flow averages 360 million l per day, 950 mld during rainy periods.) The farm grazes 15,000 cattle a year; 40,000-50,000 sheep are fattened during the spring and summer, resulting in the sale of 5,000 cattle, 36,000 sheep, and 250 bales of wool during an average year. (Melbourne and Metropolitan Board of Works)

cattle and sheep for slaughter—but the 0.02 percent condemnation rate of cattle carcasses is the same as that for the surrounding area. No higher incidence of disease among farm employees has been found to result from their employment.[16] In less well-operated sewage irrigation projects in India, however, the operators have been found to have abnormally high loads of parasites.[17]

Recycling irrigation water runoff by pumping it back to the head of the system is another way to reuse water for agriculture, but salinzation of the soil is a serious hazard (see chapter 3). Industrial wastewater may also be fit for irrigation, but it may require treatment when the industrial process adds chemicals detrimental to plant growth or public health.

Industrial Use

Municipal wastewater from secondary treatment plants can be used for cooling, ore separation, and other purposes that do not have severe water-quality requirements. Use as process-water requires advanced treatment. The degree and kind of treatment depend on demands and economics of the application. For pulp and paper production the use of wastewater after only limited advanced treatment has been found to be economically feasible.[18]

Municipal Use

Municipal use places the highest demands on water quality. Wastewater must usually undergo secondary and tertiary treatment to make it potable. Processes for removing ammonia, nitrates, and phosphates are available; residual, potentially toxic compounds and dissolved organic substances can be reduced to very low levels by adsorption on activated carbon. Dissolved mineral matter can, if necessary, be reduced to acceptable levels by ion exchange, electrodialysis, or reverse osmosis; however, adding these processes can double or triple the capital and operating costs of a conventional treatment plant.

Producing water of the necessary quality requires a large investment in capital equipment, power, and chemicals. The cost of such water is relatively high, but may be lower than that of desalted seawater (chapter 6); in arid lands it may be lower than the cost of developing alternative supplies of water, though not if treatment is needed to remove dissolved mineral salts.

Windhoek, South-West Africa, a metropolitan area of 84,000, meets its water needs by treating and recycling into the potable water supply 4 million

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[16] Ibid. Section V.

[17] Ibid. p. 147.

[18] Personal communication from National Institute for Water Research, Pretoria, South Africa (see Contacts).

however, with the planned and deliberate reuse of water, which is increasing. As demands for existing resources in water-scarce areas become even greater, its potential is highly encouraging. Although the technology for reuse is now available, economic considerations will probably limit its use initially to specialized locations or purposes. Even so, such uses may release natural sources of water for potable supplies. Ultimately, as acceptance grows, widespread recycling of wastewater into the potable supply is a definite possibility. Already, some sanitary engineers recommend adding properly treated wastewater to the potable supply, but most are cautious because of present uncertainties over the danger from viruses and heavy metals.[21]

Needed Research and Development

Because water reuse will undoubtedly be highly competitive with alternatives, it deserves a high research priority. The considerable amount of research under way has not emphasized reusing water to increase a nation's supply of water as much as at least one of its competitors, desalination. Research should center on ways to reduce cost, to combine secondary and advanced treatment processes, and to answer concerns about virological hazards.

The importance of continued research to develop treatments to reduce virological hazards, and research to determine the residual hazard after treatment, cannot be overstressed.

Research is needed to reduce the cost of tertiary treatments and to develop alternative, less expensive treatment processes. Electrodialysis and reverse osmosis show promise for removing many kinds of dissolved impurities, but better antifouling techniques and membranes that require less pretreatment are needed. Improved biological processes are needed for removing ammonia and nitrates in secondary effluents, as are new low-cost specific ion exchangers for removing mineral salts.

In the agricultural use of wastewater our biggest lack of knowledge is on the effects of long-term application. We do not fully understand to what degree continuous application of wastewater to land alters the nature of soil. We do not know the capacity of soils to absorb different metals (boron for instance) without permanent damage. Nor have we learned how to prevent or restore altered soils.

Research is also needed to develop improved management techniques and institutional arrangements whereby effluent can be substituted for potable water now used in agriculture and industry.

[21] American Society of Civil Engineers Committee on Environmental Quality Management. 1970. (See Selected Readings.)

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FIGURE 32 City of Windhoek, South-West Africa, (population 84,000) on the edge of the Namib Desert cycles its municipal wastewater through this treatment plant and back into the potable supply. (National Institute for Water Research, Pretoria, South Africa)

1/day of its sewage, which represents one-third of the total daily supply (FIGURE 32).

Advantages

The important advantage of water reuse is that it can, if properly managed, reduce by severalfold the demand on water from natural sources. Continuously recycling 50 percent of the wastewater in effect doubles the water supply.

In some arid locations reusing wastewater in industry may provide additional water needed to permit industrialization that would not otherwise be feasible.

Limitations

In any reuse scheme these major constituents of wastewater have to be considered:

Pathogenic bacteria and viruses
Parasite eggs
Heavy metals
Salts
Nitrates

Pathogenic bacteria can be killed by chlorine disinfection, but the remaining hazard from viruses after advanced waste treatment is not known. Although few outbreaks of epidemic virus diseases have been attributable to transmission in water supplies, the prevailing view is that present known treatment processes remove the hazard only if very carefully controlled.[19] Too much uncertainty exists to certify water from even advanced treatment processes as virologically safe. Though this increases reluctance to use treated wastewater for drinking or for irrigating vegetables that are eaten fresh, it should not hinder its use for less critical purposes.

To reuse water without causing environmental disaster calls for good management and a good understanding of the user's requirements. Systems can easily be mishandled and cause serious disease or harm to the environment. If more than 50 percent of the water supply is wastewater, salt accumulation can cause serious problems whether the water is for agriculture, industry, or municipal use.

> Assimilative disposal of wastes on the land, which does no permanent damage, is clearly a very different thing from uncontrolled dumping, which destroys the soil and may lead to serious pollution of ground water. Far too few engineers have a feel for proper rates of application to the soil. They forget that a little too much can change dilution to pollution. If you want to use a farm or a forest as a disposal site, there is no substitute for a good farmer or forester to manage it.[20]

The cost and difficulty of reusing water depend on the treatment processes needed. Some secondary and most tertiary treatments require large capital investment and trained, capable personnel. Operating costs are high, in many cases too high for water reuse to be feasible. In arid regions the cost structure is more favorable. Direct reuse for potable supplies may have to overcome aesthetic objections, even if the water is demonstrably pure. Furthermore, people may object to eating food grown with human waste. Reusing water will often require that all sectors—agriculture, industry, and urban administrations—be integrated in management and policy.

Stage of Development

Reuse of water has been practiced ever since people have taken water from rivers. Thus, in a sense, it is not new. Along rivers such as the Ganges, Nile, and Mississippi individuals, communities, and industry reuse the water many times over. There is no evidence that this causes harm. This chapter deals,

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[19] Malina and Sagic. 1974. (See Selected Readings.)

[20] Dean. 1971. (See Selected Readings.)

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Contacts

American Public Works Association, 1313 East 60th Street, Chicago, Illinois 60637, USA
Bureau of Sanitary Engineering, State of California, Department of Public Health, Berkeley, California 94720, USA (E. Sepp)
Central Public Health Engineering Research Institute, Nagpur, Maharashtra, India (G. B. Shende)
College of Agriculture, University of Arizona, Tucson, Arizona 85721, USA (C. B. Cluff, A. D. Day, and T. C. Tucker)
Civil Engineering Department, University of Nairobi, Nairobi, Kenya (R. Jones)
Civil Engineering Department, University of Texas, Austin, Texas 78712, USA (J. F. Malina)
Community Water Supply and Sanitation, Division of Environmental Health, World Health Organization, Geneva, Switzerland (L. A. Orihuela)
Department of Soil Science, University of California at Riverside, Riverside, California 92501, USA (A. L. Page)
Department of Water Affairs, South-West Africa Branch, Windhoek, South-West Africa (Namibia) (S. W. Burger)
Department of Watershed Management, University of Arizona, Tucson, Arizona 85721, USA (G. S. Lehman and L. G. Wilson)
Environmental Health Laboratory, Hebrew University of Jerusalem, Jerusalem, Israel (H. I. Shuval)
Institute for Research on Land and Water Resources, Pennsylvania State University, University Park, Pennsylvania 16802, USA (W. E. Sopper)
Institute for Water, Berlin, Germany (W. Niemitz)
Instituto De Inginiero Sanitaria, Universidad De Buenos Aires, Buenos Aires, Argentina (R. A. Trelles)
Melbourne and Metropolitan Board of Works, 625 Little Collins Street, Melbourne, Victoria, Australia
Municipal Treatment and Reuse Section, Advanced Waste Treatment, Environmental Protection Agency, Cincinnati, Ohio 45268, USA (R. B. Dean)
Muskegon County Department of Public Works, Muskegon, Michigan 49440, USA (J. C. Postlewait)
National Institute for Water Research, Council for Scientific and Industrial Research, P.O. Box 395, Pretoria, South Africa
Negev Institute for Arid Zone Research, Beer Sheva, Israel (J. Schecter)
Office of Water Programs Operations, U.S. Environmental Protection Agency, Washington, D.C. 20460, USA (B. L. Seabrook)
Robert S. Kerr Environmental Research Laboratory, Environmental Protection Agency, P.O. Box 1198, Ada, Oklahoma 74820, USA (C. Harlin, R. Thomas)
U.S. Water Conservation Laboratory, U.S. Department of Agriculture, ARS, Phoenix, Arizona 85040, USA (H. Bouwer)

5 Wells

Dug wells, qanats, and horizontal wells are discussed in this chapter.

Dug Wells

Hand-dug wells (FIGURE 33) have been used for thousands of years but have become less popular with the advent of tube wells.[22] Today, interest in dug wells is reviving, and they still hold much promise for arid lands. Modern materials, tools, and equipment may transform crude holes in the ground, hosts for parasitic and bacterial diseases, into more safe, soundly engineered, hygienic, and reliable sources of water.[23] Dug wells are inexpensive and easy to construct and maintain by fairly unskilled labor. They provide storage for water, as well as a source.

In most cases dug wells will be superseded by tube wells, but they provide an important transition step, and in some cases, dug wells will always be best, e.g., for shallow, low-yielding aquifers and for inaccessible regions where transporting drilling equipment is difficult.

In Afghanistan and India, dug wells are being seriously reconsidered.[24] Since about 1954, when the use of air compressors and rock drills became common, many existing dug wells on the Deccan plateau of central India have been deepened by digging through lava flows that had blocked previous equipment. In the last 10 years India has also improved many dug wells solely by adding pumps. Powered by internal-combustion engines or electric motors, inexpensive centrifugal or turbine-type pumps, installed on platforms 1–2 m above the water level, boost the water up to ground level. Suitable pumps are now made in many developing countries, including India and Pakistan.

Dug wells, however, do have distinct limitations:

- They cannot be used to reach groundwater deeper than 20–30 m.
- Their water production is usually low.
- Well-digging technology is understood and used in most countries, but the art of lining wells has regressed, and there is an important need for improved linings. The liner protects against caving and collapse and prevents

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[22] Gibson and Singer. 1969. (See Selected Readings.)

[23] Wagner and Lanoix. 1959. (See Selected Readings.)

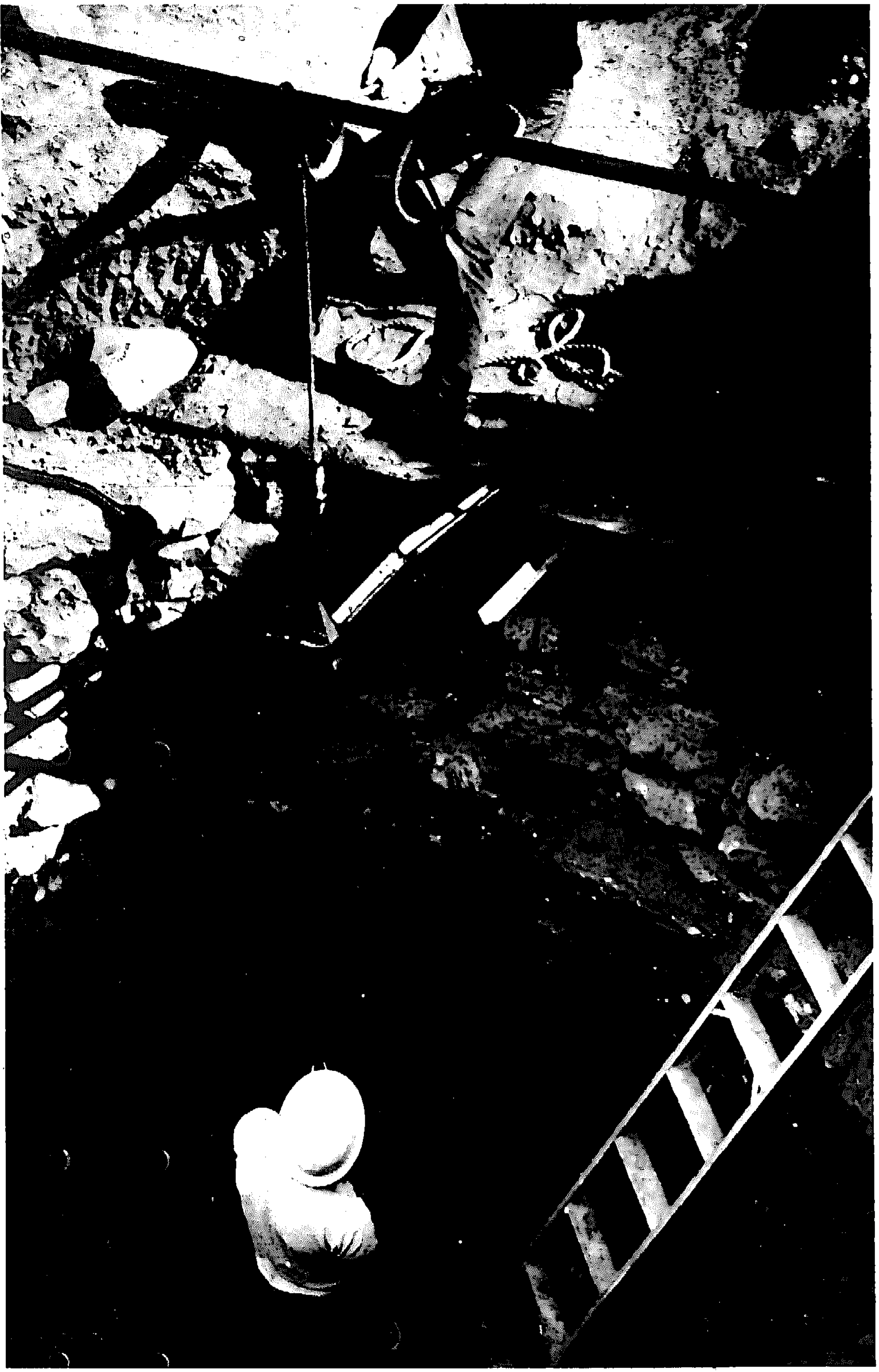

FIGURE 33 Excavation of a dug well in the Negev Desert. (U. Nessler)

polluted surface water from entering the well. The main problem is lining the walls below the level of the water table.

Another need is for safer, more rapid, more efficient digging techniques.

Qanats

A qanat is, essentially, a horizontal tunnel that taps underground water in an alluvial fan and, without pumps or equipment, brings it to the surface so that it can be used.

A qanat system is composed of three essential parts (FIGURE 34):

- One or more vertical head wells dug into the water-bearing layers of the alluvial fan to collect the water.
- A gently downward-sloping underground horizontal tunnel leading the water from the head wells to a lower point at the surface. (In part, the tunnel acts as a subsurface drain to collect water.)
- A series of vertical shafts between the ground surface and the tunnel, for ventilation and removal of excavated debris (FIGURE 35).

Because qanats deliver water without pumps and pumping costs (FIGURE 36), they can be used where pumped wells are too expensive to operate.

Qanats vary greatly in length, depending on the depth of the aquifer and the slope of the ground. The conduit from the head well to the mouth may extend 1-4 km; one in southern Iran is more than 28 km. Commonly, the length is 10-16 km. The water obtainable from individual qanats also varies; a study of 200 in the Varamin plain southeast of Teheran, Iran, measured the largest yield at 270 liters per second and the smallest at 1 liter per second.[25]

About 3,000 years ago the Persians learned to dig qanats (an ancient Semitic word and ancestor of the word *canal*) to bring mountain groundwater to arid plains. Their qanats were built on a scale rivaling the great Roman aqueducts. The system has since been used in various places from Pakistan to North Africa. In Afghanistan and Pakistan they are called *karezes*, in North Africa, *foggaras*, and in the United Arab Emirates, *falaj*. Though new qanats are seldom built today, many old ones are still used, especially in Afghanistan and in Iran, where there are some 40,000 qanats comprising more than 270,000 km of underground channels that supply 35 percent of the country's water.

In Iran areas with only 150-250 mm of annual rainfall grow their own food and even produce cotton, dried fruits, and oilseeds for export—achievements made possible by qanats. Until recently (before the Karaj Dam was built), the 2 million inhabitants of Teheran tapped the foothills of the

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[24] Government of India, Ministry of Food and Agriculture. 1962. (See Selected Readings.)

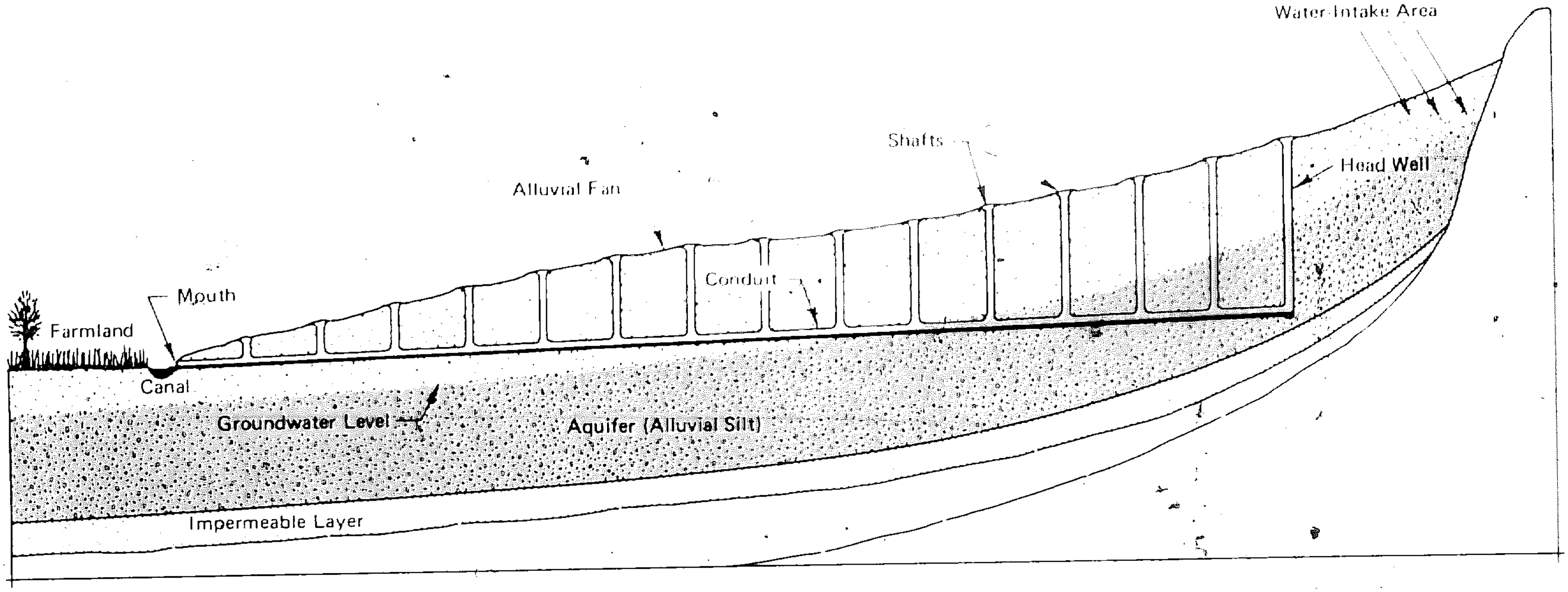

FIGURE 34 Exploiting the gradient of the natural terrain, qanat system is a series of wells dug into an underground water supply and connected by underground channels that convey water by gravity to the ground surface at lower levels. (Based on a diagram in *Scientific American*, Wulff, 1968. See Selected Readings.)

FIGURE 35 Row of craters, each marking the mouth of a qanat ventilation shaft, across an arid plain in western Iran. Crater walls protect the shafts and the tunnel below from erosion caused by the inflow of water during a heavy desert rainstorm. (FAO)

Elburz Mountains with qanats for their entire water supply. The agricultural production made possible by qanats repays the investment cost for construction and maintenance. In 1967 the return on investments from the sale of water and crops ranged from 10 to 25 percent per annum depending on the size of the qanat, the yield of water, and the crop.[25]

A recent innovation now used in Iran is a hybrid between a dug well and a qanat. A dug well is excavated to below the water table and then horizontal galleries are bored out, using the excavating methods of the qanat builders. In the dug-well shaft a centrifugal pump is then installed to pump to the surface the water collected by the horizontal galleries.

Qanats have limitations:

- They usually flow continuously and year-round, so unused water is wasted. Flow is maximum during the rainy season when the demand for irrigation is least and minimum during the major irrigation period (summer). Qanats may dry up altogether in drought years.
- They serve the lower elevations of alluvial fans, which tend to have more saline and poorer soils than do the higher elevations.

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[25] Wulff. 1968. (See Selected Readings.)

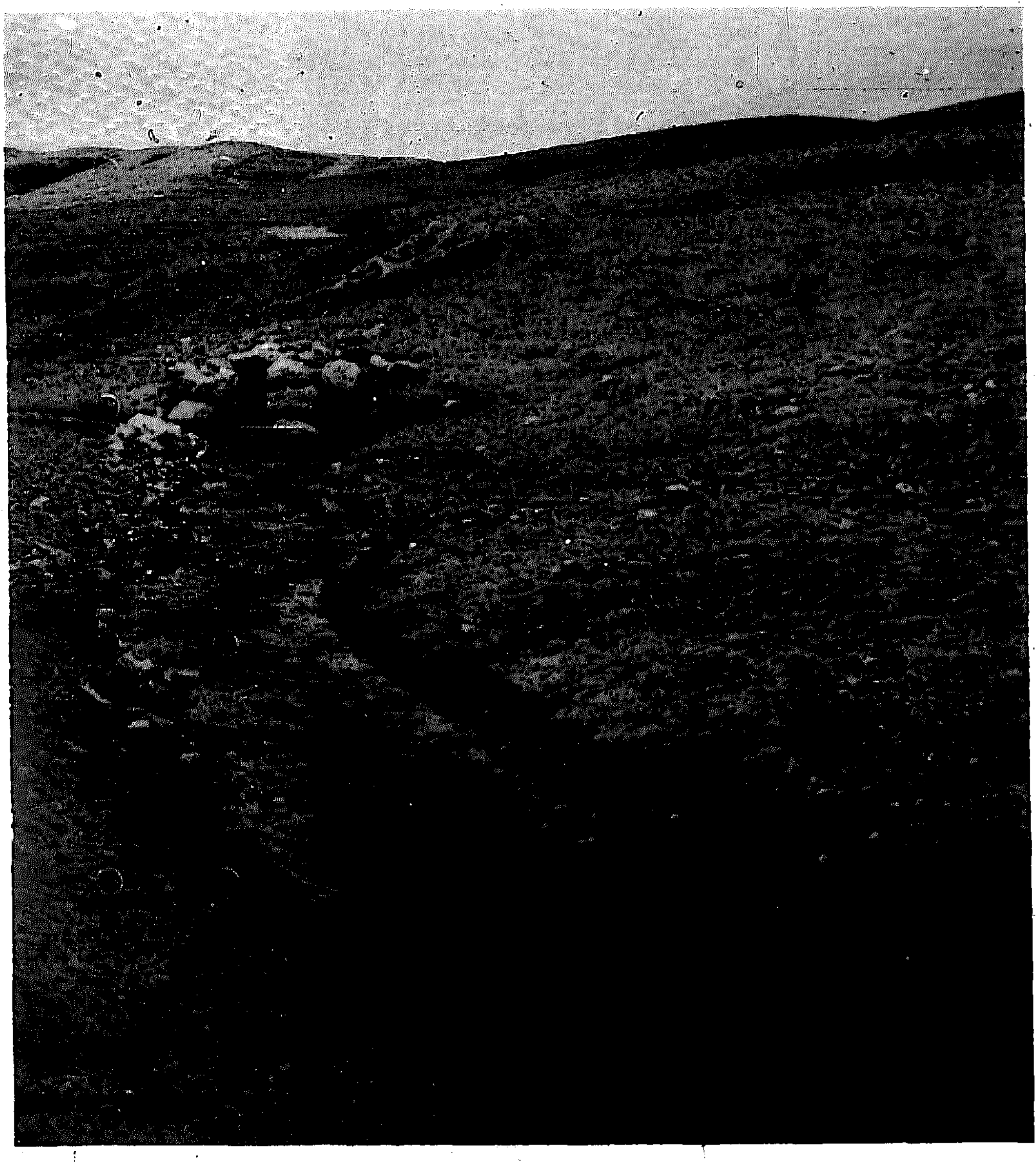

FIGURE 36 Water flowing out the main qanat of Dusadj village, Iran, is used mainly for irrigation. A qanat can deliver water in otherwise very arid terrain. (FAO)

- Qanat water is often of poorer quality than water from wells drilled higher in the alluvial fan.
- Qanats are expensive and dangerous to build by the primitive hand-tunneling methods of the past, and in recent years construction costs have increased along with rising standards of living and labor costs. However, if modern engineering, geology, hydrology, and remote sensing are applied, the qanat principle could play a role in future water production in arid lands.

Research is needed on safe construction methods, on qanat linings that increase safety and decrease maintenance, and on ways to shut off the water flow when it is not needed.

FIGURE 37 A completed horizontal well on test yields over 50 gpm. Plumbing head includes two tees, a shutoff valve to regulate the flow, a vacuum relief, and a pipe reducer. (W. T. Welchert)

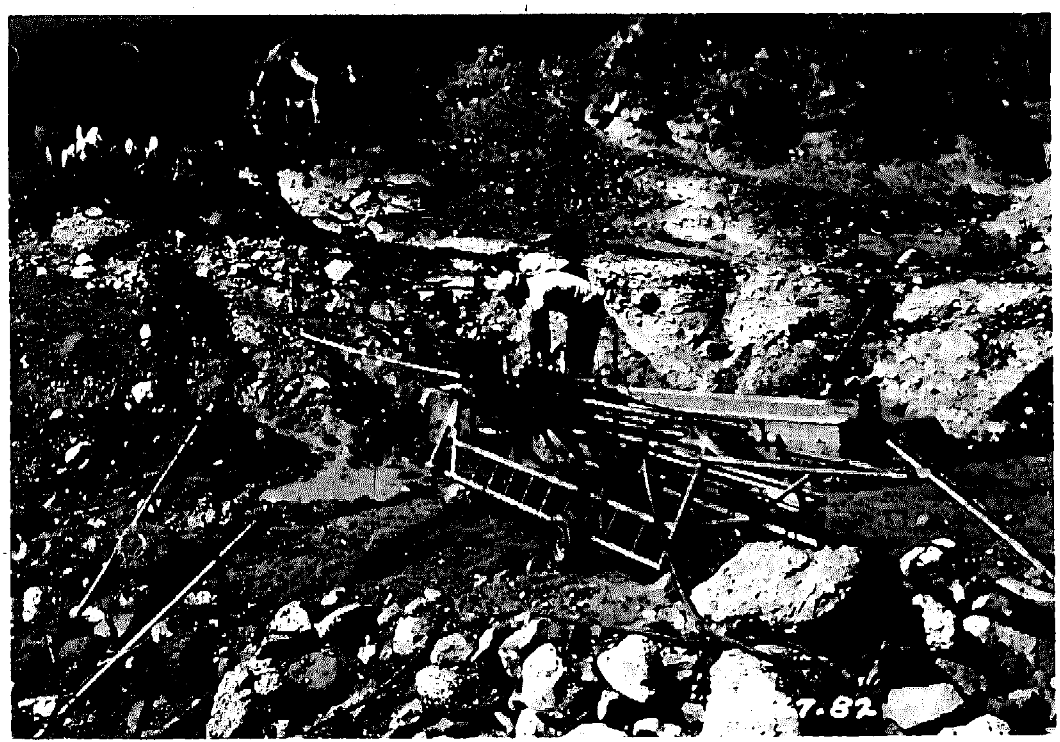

FIGURE 38 Drilling a horizontal well. A standard well casing is drilled on a slight downward slope. Equipment is light and portable and easily transported even in remote, rough terrain. (W. T. Welchert)

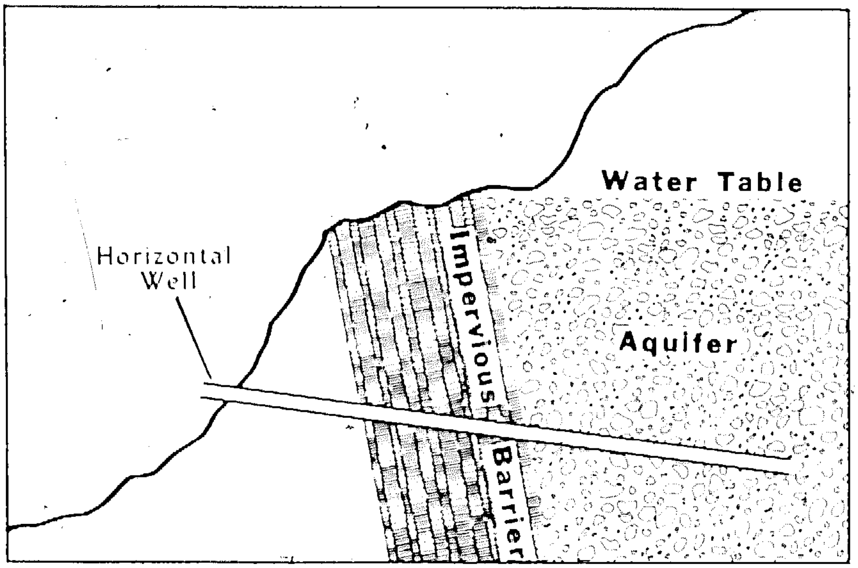

FIGURE 39 Good sites for horizontal wells are dike formations, impervious geologically tilted clay, or rock walls that form a natural dam. (W. T. Welchert)

Horizontal Wells

In the development of water supplies, small springs are often neglected. Yet in many remote and arid mountain regions, springs are the safest and most dependable source of water for domestic use. The horizontal well system, an improved spring-development process, has great potential for providing and conserving sanitary water in geologically appropriate areas.

A horizontal well is a "cased" spring (FIGURE 37). A horizontal boring rig (FIGURE 38) is used to drill a hole and install a steel pipecasing into a mountain or hillside to tap a trapped water supply (FIGURE 39).

Tapping water from springs is an ancient art. Conventionally, when a seep or spring is located, it is either dug or dynamited to expose the water-bearing rock. Results are erratic and always carry a risk of damaging the natural barrier that dams the underground reservoir. The flow, once established this way, is almost impossible to control and may result in rapid depletion of the aquifer.

Horizontal wells virtually eliminate these hazards. They are drilled at promising sites where springs, seeps, or traces of water are found. Occurrence of phreatophytes (chapter 13), dried-up springs, and favorable geology are all indicators used to select the drilling site. A horizontal well can tap the aquifer with precision and safety. Furthermore, it protects against contamination by animals, dust, erosion, etc. No pumps are needed. Maintenance costs and problems are insignificant in comparison to those of other systems for harnessing springs.

If the flow is very low, a storage tank can be added to accumulate water during the night or off-season. With adequate storage, spring sites that flow only during a few weeks in the year may be useful.

During the last 15 years about 2,000 successful horizontal wells have been drilled in arid areas of the southwestern United States. A 1967 University of Arizona study indicates that a serviceable water supply was obtained at 45 out of 53 locations tried during one program. Successful yields varied from 1-230 l/minute; most were in the 10-40 l/minute range. Drilling time averaged 32.3 hours per producing well.[26]

Horizontal drilling equipment is currently manufactured; it is simple, portable, and dependable. The drilling process involves a rotary, wet-boring horizontal drill stem rig (FIGURE 38), a carbide-tipped or diamond-core drill bit, a small recirculating water pump, a cement slurry pressure tank, a drill water supply, and a few standard plumbing tools and supplies.

Horizontal-well drilling is quite a different technology from vertical drilling. Skill, patience, and field experience are required to master it.

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[26] Welchert and Freeman. 1973. (See Selected Readings.)

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Ministry of Agriculture, Government of India, Krishi, Bhawan, New Delhi, India (J. K. Jain, Irrigation Adviser)
Servico especial de Saude Publica, Government of Brazil, Brasilia, Brazil
University of the Negev, Beer Sheva, Israel (A. Issar)

Horizontal Wells

Cooperative Extension Service and Agricultural Experiment Station, University of Arizona, Tucson, Arizona 85721, USA (W. T. Welchert)

6 Other Sources of Water

This chapter briefly mentions some other sources of water in arid lands that are either more than adequately described in literature elsewhere or too highly-speculative to warrant more specific treatment in a general report.

Groundwater Mining

Many productive aquifers in arid regions of the world are storing large quantities of water that can be tapped by well-known deep-well extractive techniques. Aquifers of this type are widespread beneath deserts in northern Mexico, southwestern United States, North Africa, eastern Saudi Arabia, the Sinai, and elsewhere in southwest Asia. The water in such aquifers is not naturally replaced once it is withdrawn; it must be considered a "wasting asset" like any other mineral commodity. Its development must be undertaken with the full understanding that usually within a few decades the supply will be depleted and capital investments must be amortized within that time. Under some conditions these aquifers may provide interim supplies to generate capital to underwrite expensive systems that bring in a more permanent supply of water from outside the region. Development of such aquifers is now proceeding in several parts ~~of~~ Algeria, Libya (FIGURE 63), Egypt, Saudi Arabia, Mexico, and the United States.

Desalting

Low-cost desalting of seawater would be a boon to arid lands bordering seas or salt lakes; over the past few decades many proposals to build huge distillation plants to produce water for agriculture have been widely advertised and intensively promoted. Although new and improved desalting methods using membranes and ion exchange have been developed, no method can yet promise truly low-cost freshwater. Current promises of cost reduction for distillation plants are based on the assumption that the cost of the product decreases as the size of the plant increases. But a practical limit exists to cost reduction achieved by this means. Also, there are problems in disposing of huge quantities of hot brine, pumping and conveying desalted water to the point of use, and storing it until needed for irrigation. Another fundamental problem is that desalting plants require large amounts of energy to construct and operate.

Most proponents of desalting schemes now agree that the water will be too expensive for use in irrigation as practiced today. However, desalination of sea or brackish water could prove economically rewarding in special situations such as tourist centers.

Distillation plants producing up to several million gallons per day are commercially available and are already used for domestic and industrial purposes in some very arid regions where the local economy can afford it.

Solar Distillation

In solar distillation the sun's radiation passes through a transparent cover on to a source of brine; water evaporates from the brine; and the vapor condenses on the cover which is arranged to collect and store it. It was first used in Chile's Atacama Desert in 1872 in a plant supplying drinking water for livestock used in nitrate mining. The plant reportedly operated for 30 years.

The process today is generally in the pilot stages, though small community-scale stills are close to extensive commercial application. Durable designs requiring little day-to-day attention and operating with minimal maintenance have been developed in the United States, France, Spain, and Australia (FIGURE 40). Solar distillation is now used on a small commercial scale to supply small towns in isolated areas of Australia and small communities in the Mediterranean basin and the Caribbean. Modern research into solar distillation is emphasizing new materials and designs for economical and durable construction to reduce product-water cost.

Remote Sensing for Detecting Water

The use of photographs from satellites and high-flying aircraft is a newly developing tool that is proving useful for planners in arid lands. The following are a few successful uses of such remote sensing.

- Open-water oases have been detected, and repetitive imagery has been used to determine their transience.
- Geological information for determining the shape and extent of underground aquifers has been obtained from most types of remotely obtained imagery, including radar, thermal, and optical images from aircraft or

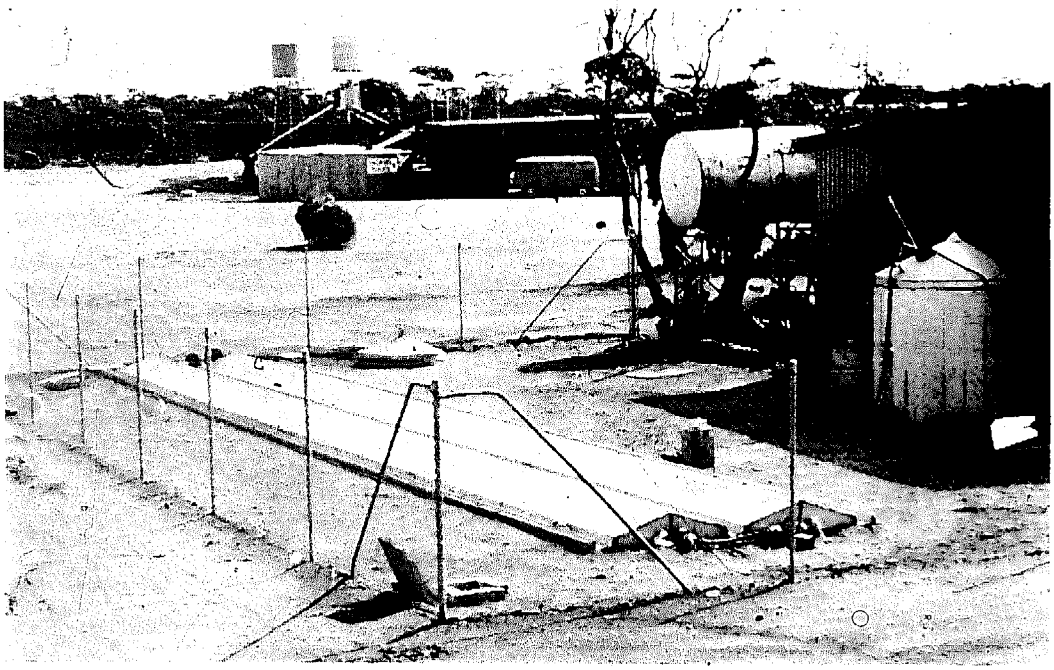

FIGURE 40 Solar still at Caiguna, Western Australia. Waste heat from a nearby internal combustion engine supplements the solar heat, markedly increasing the still's efficiency. (Commonwealth Scientific and Industrial Research Organization, Highett, Victoria, Australia)

satellites. Airborne geophysical sensors, such as magnetometers, are also useful in mapping underground structures that control groundwater movement and distribution.

- The extent of springs, seeps, and shallow groundwater in alluvial channels is often mappable, even from satellites, because trees and shrubs associated with moisture can be detected.
- Effects of rainstorms on the desert can be detected; after a storm, the darker tones of the moist soil can be seen, and a few weeks later vegetation responding to the moisture is revealed.
- Plumes of freshwater from offshore submarine springs can be detected with the use of thermal scanners because they usually differ in water temperature from the surrounding sea.
- The extent and movement of floodwaters have been mapped.
- The snow cover on mountains has been determined in order to estimate the amount of runoff water that will be available at lower altitudes after the thaw.

The following topics are included solely to give some cautions and a sense of the range of current speculation about water supplies for the distant future.

Rainfall Augmentation

Certain cloud formations contain supercooled water; rainfall augmentation hastens precipitation of this water. Adding ice, frozen carbon dioxide, and silver iodide—whose crystal shapes promote condensation (nucleation) of supercooled water—causes dramatic ice-crystal formation and produces rain. This method is known as cloud seeding.

To produce rain by cloud seeding, one must always have the right meteorological conditions. Even then the seeding "can sometimes lead to more precipitation, can sometimes lead to less precipitation, and at other times the nuclei have no effect."[27]

Though there is keen interest in cloud seeding in arid lands, experience indicates that its best opportunities for increasing precipitation are in areas where cold, wet air masses are swept upward over mountain ranges. Prospects for increasing precipitation over low-lying arid lands do not seem promising, primarily because of the scarcity of water-rich clouds. Arid lands that benefit from cloud seeding will probably be those fed by streams originating in mountains.

The results of cloud seeding are difficult to predict because of the still imperfect knowledge of the physical processes causing precipitation and because of engineering difficulties in getting seeds into clouds in optimum amounts and at the right time and place. A related uncertainty is whether seeding clouds in one area modifies precipitation in another. Detailed physical analysis of some cloud systems may, in the future, allow one to predict the effects of cloud seeding, but research is in the very early stages.

Icebergs

Eighty-five percent of the world's freshwater is trapped as ice in the polar regions, but it is generally considered unusable. Engineers, glaciologists, and physicists are now speculating on whether it could be profitably recovered by towing icebergs to water-short regions. According to some, "the idea appears both technically feasible and economically attractive and merits serious consideration."[28] Data on size and distribution of icebergs indicate that the supply is more than adequate, and satellites can be used to select suitable icebergs. Prime producing sites in the Antarctic could supply icebergs for Australia, the Atacama Desert in Chile, and other arid regions of the Southern, and perhaps even the Northern, Hemisphere.

[27] Committee on Atmospheric Sciences, National Academy of Sciences–National Research Council. 1973. (See Selected Readings.)

[28] Weeks and Campbell. 1973. (See Selected Readings.)

The icebergs are there; the problem is to move them. According to one report,[28] a hypothetical supertug, which could be built with present technology, could tow icebergs up to 16 km long, 3.5 km wide, and 200 m thick. On delivery, the water in such icebergs would be worth hundreds of millions of dollars.

Melting losses are important because transit times at reasonable towing speeds may exceed 100 days and water temperatures at the delivery sites exceed 15°C. Unfortunately, detailed calculations and adequate field observations to accurately predict towing speeds and melting rates still need to be done.

Two inherent problems are getting the ice to melt at the end of the tow, and pumping the water from sea level into the supply system. Perhaps the ice could provide a "cold sink" for coastal powerplants; thus, waste heat would be utilized for melting ice and the thermodynamic efficiency of the powerplant increased.

As with other water-resource exploitation proposals, critical technology assessment must precede any decision that iceberg harvesting is a realistic, desirable possibility. In particular, iceberg-harvesting proposals raise international legal and political questions concerning resource rights—matters of uncertainty in the delicate Antarctic Treaty regime and matters of very intense negotiation in the emerging restructuring of the law of the sea. Additionally, as the importance of the polar regions to world climate has become increasingly evident, it has become equally evident that not enough is known of the physical basis of climate to permit confident prediction of the extended effects of even apparently small modifications of the polar ice environment.

Dew and Fog Harvesting

The possibility of condensing water from the atmosphere by some simple scheme has intrigued several investigators. Some have suggested that ancient civilizations accomplished it for agricultural purposes. "Dew mounds" in the Negev (FIGURE 4) and the ancient "aerial wells" of Theodosia in the Crimea were piles of rocks that supposedly cooled during the night and condensed the early morning dew. Experiments have been unable to show that this process occurs to any significant extent, and the supposed dew mounds of the Negev have now been shown to result from soil-smoothing operations to increase rainfall runoff[29] (chapter 1). Dew will condense on piles of rock, but not in harvestable and usable quantities.

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[28] Weeks and Campbell. 1973. (See Selected Readings.)

[29] Evenari, Shanan, and Tadmor. 1971. p. 127. (See Selected Readings.)

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Part II

Water Conservation

7 Reducing Evaporation from Water Surfaces

Reservoirs and canals in arid lands are subject to heavy evaporation losses, but because evaporating water is invisible these losses are often not recognized. From small reservoirs, stock tanks, and farm ponds with large surface areas open to the air (compared to the volume of water stored), evaporation losses often exceed the amount of water used productively.

Reducing evaporation is an important way to increase the supply of water. It increases reservoir capacity without new construction; in arid regions it may mean the difference between a dry reservoir and a filled one.

Methods

Generally, the method for reducing evaporation has been to cover the water surface with a barrier that inhibits vaporization. On small tanks, a cover or roof is an obvious choice, but for ponds and larger reservoirs the solution is less simple. For the latter the methods tested include the following: liquid chemicals that automatically spread out, forming a sealant layer across the surface; blocks, rafts, or beads that float on the water surface and reduce the area where vaporization can occur; and storing the water in sand- and rock-filled dams.

Liquid Chemicals

Aliphatic alcohols, e.g., cetyl alcohol, are long slender molecules that align themselves side-by-side on a water surface, covering it to form a film 1 molecule thick. Considerable research and publicity have been devoted to the possibility of using such films to reduce evaporation from water surfaces. Unfortunately, the films do not reduce the amount of solar energy the water absorbs, and they decrease the amount of heat normally lost from the water because inhibiting evaporation also inhibits the cooling effects of vaporization. Although evaporation decreases where the alcohol layer is intact, the higher water temperature increases evaporation at any part of the water

FIGURE 41 An experiment in Arizona, USA, using wax to suppress evaporation. Blocks of wax have been added to the tank (foreground). Sun's heat melts the wax to form the continuous film visible on the tanks in the background. During 4 years this film has suppressed over 85 percent of the normal evaporation. (K. C. Cooley)

surface the barrier does not cover. Furthermore, an intact alcohol barrier is impossible to maintain because of wind and wave action. These problems make the method impractical today.

The aliphatic alcohol molecular monolayer is, nonetheless, a tempting and potentially rewarding concept: it requires only small amounts of materials (less than 60 g per ha of water surface); it reportedly does not restrict the transmission of oxygen to the water; and it consists of materials that are nontoxic to fish or humans. Attempts are now under way to circumvent the problem of maintaining a continuous film on the water surface. One approach uses a plastic net to restrict the drift and disruption of alcohol layers.

Wax

Wax is an unusual, recently tested evaporation suppressant. Floating blocks of wax are added to the water; in sunlight they soften and flow to form a flexible, continuous film. In Arizona, a wax cover on a small tank (FIGURE 41) is still in good condition after 4 years; the evaporation-suppressing efficiency is over 85 percent. Even if the film cracks and breaks during cold weather, the sun's heat subsequently re-forms it.

FIGURE 42 Protective covering of molded, lightweight, concrete slabs cut evaporation by an estimated 80 percent recently in full-scale tests on two reservoirs in Ovamboland, South-West Africa. Engineers cover reservoirs with 24-in², 2-in thick floating slabs of polystyrene, sand, and concrete. Exposed surface of each slab is painted white to reflect the intense sun rays, which hasten evaporation.

The specific gravity of the material (0.8) keeps about 80 percent of the floating slab submerged, reducing the possibility of piling up in heavy winds. Submerged portion of the slab is coated with bitumen for durability and to prevent the material from affecting the taste of the water. Slabs have rounded corners to permit the large body of water underneath to breathe properly when covered with the densely packed slabs. (National Institute for Water Research, South Africa)

Solid Blocks

Floating materials, covering the water surface, reduce the area where evaporation can occur. Blocks of lightweight concrete, polystyrene, wax, rubber, and plastic are under trial as evaporation retardants. Floating concrete blocks, made with lightweight aggregates, have been used to reduce evaporation from a 10,000 m^2 reservoir in South-West Africa[30] (FIGURE 42).

To overcome the water heating that is an inherent problem in evaporation suppression, researchers are working with floats made of insulating and light-colored reflecting materials that prevent solar energy from entering the water. For example, sheets of inexpensive and highly insulating expanded-polystyrene, 2.5 cm thick and coated with asphalt and gravel have been

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[30] Concrete slabs cut reservoir losses. 1966. (See Selected Readings.)

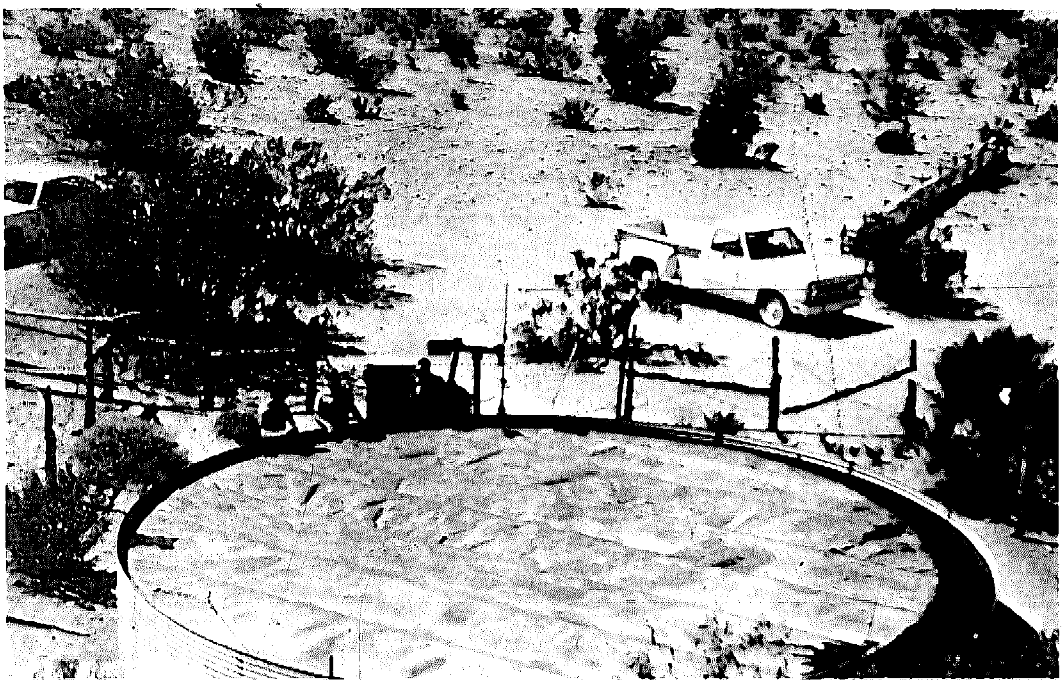

FIGURE 43 Floating foam-rubber sheet (9 m diameter, 5 mm thick) covers a water-storage tank near St. George, Utah, USA. Experience to date suggests that the cover will last 10 years with an evaporation-control efficiency of 80-90 percent. Estimated cost of the water saved in a 120-cm/year evaporation zone is US$1.80-$2.00. (U.S. Department of Agriculture)

tested. Coupled together with inexpensive clamps to form large rafts up to 160 m^2, they can form excellent energy and vapor barriers. (See FIGURES 24, p. 33; and 43.) Foamed butyl rubber can also be effective; though expensive, it may last for over 10 years.

Sand-Filled Reservoirs

Evaporation can be controlled by filling reservoirs with sand and loose rock. Water is stored in the pores between the particles, and the water level is kept more than 30 cm below the surface to shield it from evaporation (see gravel mulches, chapter 9). Recently, two small, plastic-lined tanks were built near Safford, Arizona, and filled by commercial rock-picking machines. The rocks reduced the tank's volume by 55 percent, but they reduced evaporation by 90 percent.[31] Another related technology is the sand-filled water storage tank developed in the Sudan for use with rainwater harvesting (FIGURE 11).

Small sand-filled dams have been used in the Namib Desert since 1907 for supplying drinking water to livestock. They can store water for long periods, much longer than conventional open storage. They can provide water during

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[31] Cluff, et al. 1972. (See Selected Readings.)

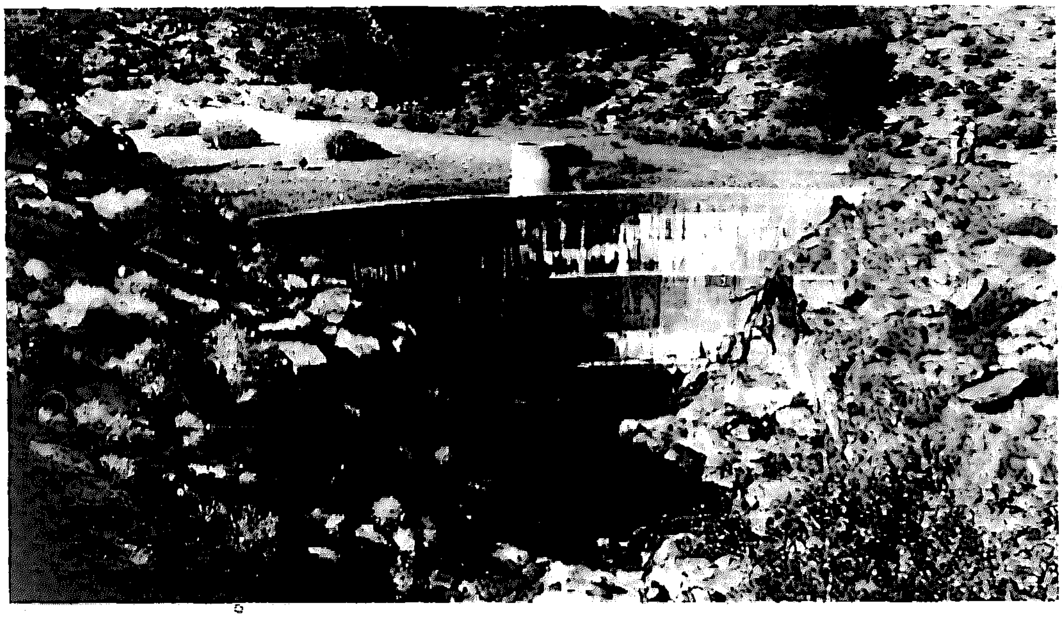

FIGURE 44 Sand-filled storage dam in South-West Africa built of concrete. Staged construction is clearly visible. Well shaft behind the dam wall is used to extract the water. The dam size can be judged from the persons at right. (O. Wipplinger)

years of total drought; when the water table is 1 m below the sand surface, evaporation ceases for all practical purposes.[32] The water is drawn off by a drainage pipe through the dam wall or by a well dug into the sand (FIGURES 44 and 45).

The dam wall is built across the riverbed during the dry season; later, the river floods will deposit the necessary sand and gravel. Normally, the soil carried by flood waters is 3/4 sediment and mud and only 1/4 sand and gravel. A dam trapping all of this mixture would quickly silt up. To ensure that only sand and gravel are deposited, the dam wall is heightened in stages of only 1 m (though the first is usually about 2 m). Floodwaters deposit heavy gravels and sand, but silt and soil are carried over the top by the speeding waters. Each 1-m stage is added when the dam is filled with sand and gravel (which may require a complete wet season) until the operating height of 6–10 m is reached.

Sand dams are particularly effective when built over fissures that lead underground to natural aquifers, for the dam can slow rushing floodwaters enough to get the aquifer recharged (chapter 16).

A simplified approach to this method is to use a pump and a well-shaft system that can be readily sunk into dry riverbeds to extract water stored naturally in the sand a few feet below the surface.[33]

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[32] Wipplinger. 1958. (See Selected Readings.)

[33] Ball and van Rynveld. 1972. (See Selected Readings.)

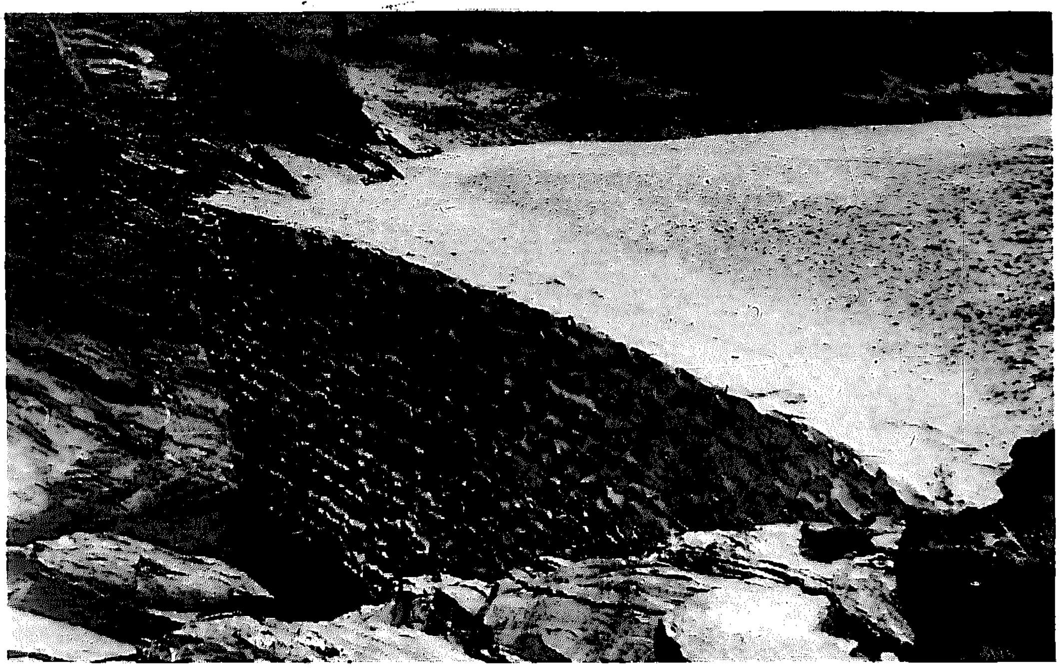

FIGURE 45 Sand dam in South-West Africa built of rock and mortar. (O. Wipplinger)

Advantages

Evaporation control is a particularly important way to conserve water because it usually requires little new construction and the additional water becomes available without construction delays. In many cases it will cost less to reduce evaporation than to collect and store an equivalent amount of water from other sources. Some of the better materials have provided water for less than U.S.$0.025 per m^3 in a 200-cm-per-year evaporation zone.[31]

Evaporation is greatest during the driest seasons, which are also the peak periods for water use. Controlling only dry-season evaporation with short-lived methods could have economic significance in arid lands.

Suppressing evaporation in impounded waters also suppresses the increase in salt concentration that occurs with evaporation. Floating evaporation-control materials cut off the light, thereby reducing the growth of undesirable algae and submersed aquatic weeds.

Limitations

At present, evaporation suppression is limited to small storage facilities such as ponds, tanks, troughs, and oases. In practical terms large reservoirs,

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[31] Cluff, et al. 1972. (See Selected Readings.)

lakes, and rivers are still beyond the reach of available technology because it is very difficult for the evaporation-suppressing system to survive heavy winds, storms, and floods.

The effects of evaporation-control methods on animal life in the water may not be important in small containers, but they should be considered in reservoirs.

Sand storage dams can be built only where the geology permits. The floodwaters must contain gravel and sand (coarse or fine granite, quartzite, microschist, and dune sand all work well), and the dam site must be made absolutely watertight (e.g., cement-grouted to stop seepage if necessary). To build a sand dam requires patience, time, and logistics that can cope with delays while each stage of the dam wall is built, because often only one stage can be added each year. For this last reason the technology has not yet been widely accepted.

Seepage control (chapter 8) is usually easier and cheaper than evaporation control; therefore, evaporation control should not be considered for a reservoir or water-distribution system until seepage is controlled.

Stage of Development

Hydrologists and engineers have long been aware of the quantity of water in arid lands lost each year by evaporation, but evaporation suppression is still experimental. By far the greatest number of studies have been concerned with alcohol films. Although research conducted on the use of solid floating materials is limited, progress has been considerable. This method appears to offer the most promise for small storages. Sand dams have been built by the score in South-West Africa during the past 50 years. A few have also been built in Kenya and other countries of East Africa.

Needed Research and Development

No economical method exists for reducing evaporation from large, multipurpose reservoirs; research in this area is desparately needed.

Extended field trials are needed to test the practicality of the floating covers, such as expanded-polystyrene rafts or wax layers on water reservoirs. These do not require any special equipment or skills and can be readily introduced into arid lands for pilot testing.

Research is needed to overcome the mechanical difficulties of stabilizing any evaporation-control system on water surfaces subject to wind, wave, and currents. This is particularly so for the alcohol monolayers.

It is likely that some radically different approaches to evaporation control await discovery; research into novel methods is encouraged.

The sand storage dam is a technology that needs field testing in many arid areas. Research is needed into its rational design, e.g., for the height of stages in relation to the extent of the catchment.

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Contacts

General

Department of Agricultural Engineering, Oklahoma State University, Stillwater, Oklahoma 74074, USA (F. R. Crow)

Director of Water Affairs, Kaiser Street, Windhoek, South-West Africa

U.S. Water Conservation Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Phoenix, Arizona 85040, USA (K. R. Cooley)

University of New South Wales, Kensington, New South Wales, Australia (G. J. Wiesner)

Victorian State Rivers and Water Supply Commission, Victoria, Australia

Water Resources Research Center, University of Arizona, Tucson, Arizona 85721, USA (C. B. Cluff)

Sand Storage Dams

Department of Civil Engineering, University of Stellenbosch, Stellenbosch, South Africa (O. Wipplinger)

Department of Conservation and Extension, Ministry of Agriculture, P.O. Box 8108, Causeway, Salisbury, Rhodesia (J. S. Ball)

Hydraulic Research Laboratory, C.S.I.R., P.O. Box 395, Pretoria 0001, South Africa

Illinois State Water Survey, Urbana, Illinois 61801, USA (W. J. Roberts)

8 Reducing Seepage Losses

For economic reasons most arid lands are forced to use earthen canals and reservoirs. Because their soils are often porous, many of these storage facilities and conduits suffer serious water losses through seepage. In diverting water from its intended purpose, seepage can also cause serious waterlogging, salinification, and erosion of neighboring soils.

Seepage can be reduced if the walls of reservoirs and conduits are made watertight. Recent technology has produced many inexpensive, waterproof materials that may prove valuable for this purpose.

Of the various ways to reduce seepage, only some of the newer, low-cost methods are discussed in this report.

Methods

Many ways to make soils impervious for rainwater harvesting (see list in chapter 1) can also be used to reduce seepage in waterways - soil compaction, chemical treatment of soil, and soil covers such as butyl rubber, sheet plastic, asphalt reinforced with plastic or fiberglass; and ferrocement.[34]

Much seepage is caused by calcium in the soil. Calcium causes clay to bunch up (aggregate), forming cracks and a porous structure that lets water seep through easily. In this situation seepage can be greatly reduced by treating the soil with a sodium salt such as sodium carbonate (FIGURE 46). Sodium breaks up clay aggregates (FIGURE 47) and causes clay particles to swell and plug the soil pores (FIGURE 48). This method can be successful only where conditions are favorable (e.g., the soil must have a minimum of 15 percent clay, be at least 30 cm deep, and have the chemical capacity to exchange calcium for sodium ions.)

Shallow earthen, but rock-free reservoirs (less than 3 m deep) can be made watertight with low-cost polyethylene and polypropylene films, but deeper reservoirs or those built on stony soils require thicker and tougher films of vinyl or reinforced polypropylene. In both cases the films should be

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[34] See, for example, *Ferrocement: Applications in Developing Countries.* (Available without charge. See publication 8, p. 152.)

FIGURE 46 Cracked soil structure indicates high calcium content in a dry pond bed in Coconino National Forest, Arizona, USA. Water seeps away through the cracks; original seepage loss in this 1,000 m^2 stock-watering pond was 5-12 cm per day. The dry pond was cleared of rocks and weeds and 1 ton (about US\$80 worth) of sodium carbonate applied by hand. This was then mixed with the soil to a depth of about 8 cm with a small tractor and disk, and . . .

FIGURE 47 . . . in this soil from the same pond after treatment sodium carbonate has caused the clay aggregate to break down into fine particles that retard seepage. . . .

protected with a covering of soil or gravel. In Europe and the United States butyl rubber is increasingly used to line reservoirs, water channels, and storage tanks. It is strong, durable, weather and pest proof, but it is an expensive way to reduce seepage.

Concrete-based materials, such as cement-stabilized soil, ferrocement, and concrete-filled fabric also have potential.

One problem encountered in lining reservoirs is stabilizing the banks. Soil is usually unstable on slopes greater than 1:3. Steeper slopes are desirable, however, to maximize storage, minimize evaporation losses, and inhibit weeds. Promising methods of providing a revetment to protect steep banks include the use of used rubber tires, ferrocement, and soil cement packed into sausage-shaped plastic bags (FIGURES 10-12, pp. 19-20). Near-vertical slopes can be constructed with sausage revetments. Local soil is blended with a small amount of cement and moistened through pinholes made in the plastic tube. The sausages are stacked in place tightly and allowed to set.[35] This technique is also suitable for canal and ditch revetments.

Advantages

Any reduction in seepage provides additional water without requiring new equipment or facilities, and most methods do not interfere with use of the

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[35] Intermediate Technology Development Group, Ltd. 1969. (See Selected Readings.)

FIGURE 48 . . . Seepage then dropped to 0.4 cm per day. After a "booster shot" of 200 kg of sodium salts (33 months after the initial treatment) this low seepage rate has been maintained in the pond for 5 years. (U.S. Department of Agriculture)

impoundment for recreation, fishing, etc. In some areas reducing seepage prevents associated problems such as waterlogging and salinification of the surrounding soil. Lining canals also reduces maintenance and weed-control problems.[36]

In general, reducing seepage losses in reservoirs and conduits is easier and more economical than reducing evaporation losses (chapter 7).

Limitations

The primary disadvantage of seepage control is its cost.

In most methods maintenence of the lining is a constant concern because even small holes can allow large amounts of water to drain away, especially if the surrounding soil is porous.

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[36] For a discussion of aquatic weed problems see publication 11, p. 153.

Stage of Development

Seepage control has been practiced in arid lands since the beginnings of civilization. However, most of the techniques discussed in this chapter—including the use of sodium salts, plastic sheeting, and butyl rubber—have been used within the last 20 years and are commercially available. Reinforced asphalt has been under test for approximately 10 years. The use of inexpensive polypropylene is a recent development, not yet extensively tested or utilized. Ferrocement, virtually untested for this purpose but known to be watertight, holds great promise because it can be constructed by unskilled labor using materials available in developing countries.

Needed Research and Development

There is a major need for widespread field trials, particularly in arid developing countries, to test and compare the effectiveness of different systems and consider the economics of their application.

New, more economical materials are needed, for they could make seepage control possible worldwide. As new watertight membrane materials become available, their use in this application should be evaluated.

Improvements in sealing and laying underground moisture barriers (chapter 12) could bring major breakthroughs; a watertight seal could be laid directly in the soil where it is protected from mechanical damage and weathering.

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Contacts

Plastics (and agricultural) supply houses in some countries should have in stock materials suitable for lining ponds and conduits. Some agricultural supply houses also carry sodium and phosphate salts for pond sealing. The following are involved in research developments:

Bamangwato Development Association, Radisele, Botswana

Doxiadis Ionides Associates, Ltd., Ripley, Surrey, England

Intermediate Technology Development Group, Ltd., Parnell House, 25 Wilton Road, London SW1V 1JS, England

Water Resources and Development Service, Land and Water Development Division, Food and Agriculture Organization of the United Nations, Via delle Terme di Caracalla, 00100, Rome, Italy

Water Resources Research Center, University of Arizona, Tucson, Arizona 85721, USA (C. B. Cluff)

9 Reducing Evaporation from Soil Surfaces

Evaporation from soil surfaces wastes large amounts of water—an important consideration in arid lands where low humidity greatly encourages evaporation. From one-fourth to one-half of the water lost from a crop is evaporated from the soil surface.[37]

This loss can be reduced and irrigation water saved by placing watertight moisture barriers or water-retardant mulches on the soil surface.[38] In many cases these barriers will also stabilize loose soils, ~~stop desert~~ encroachment, allow runoff agriculture, aid in landscaping, or reduce salinity buildup.

Suppressing evaporation from the soil conserves water where its effect is great: within the root zone of the plant. In an arid region small water savings here may be more important to a crop's survival than large improvements at earlier points in the water supply.

Methods

Some soil-surface moisture barriers are made of nonporous materials such as paper, asphalt, ~~latex~~, oil, plastic film, or metal foil, but a 5–25 mm thick layer of porous material can also substantially reduce evaporation. Water and water vapor move so slowly through a dry, porous material that soil moisture is retained. In practice, suitable porous materials are plant residues such as straw, sawdust, wood bark, or cotton burs, as well as gravel, sand, or cinders.

Plant Residues

Planting directly into the standing residue of the previous crop is one way to retard evaporation (and reduce erosion) because the residues and hard soil surface provide a better moisture barrier than the loose surface left after

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[37] Viets. 1966. p. 270. (See Selected Readings.)

[38] Also by creating windbreaks of trees, fences, or taller growing plants—a well-known and highly site-specific method not dealt with in this report. (see also FIGURE 50)

ploughing. This is known as minimum tillage (FIGURE 49). Because weeds that would normally be buried by the plough become more of a problem with this method, stringent weed control (with herbicides or hand labor, but not methods that destroy the soil surface) is essential for its success. Sometimes the soil surface may have hardened enough to retard all water penetration and chiseling may be necessary to get enough moisture to the root zone.

Plant residues such as straw and cotton burs spread on the soil also retard evaporation. Water and soil conservation is greatest when the residues cover 90 percent or more of the soil surface. The amount of crop residue needed for this is about 1.5 tons/ha in the case of straw and 11 tons/ha for cotton burs. For residues spread on the soil surface, the greatest reduction in evaporation comes with the first 5 mm of thickness.

Gravel Mulches

Infiltration of water into soil and the conservation of soil moisture are greatly improved by gravel mulches, even in layers as thin as 5 - 10 mm. They

FIGURE 49 Minimum tillage in Texas, USA. Grain sorghum is planted on both sides of row of cotton stalks. After sorghum is harvested, new cotton will be planted between the rows of sorghum stubble. (U.S. Department of Agriculture)

reduce erosion by wind and water; if light colored, they cool and if dark colored, they warm the soil. Either in the right environment can benefit plant growth.

The chief problems are cost, the need to periodically redeposit the gravel on the surface, and interference with mechanized planting and cultivation. A machine developed to lay gravel-covered plastic catchments (chapter 1) can be used to separate the gravel and lay it on top of the soil as it passes.

In arid Lanzarotte, in the Canary Islands, black volcanic ash is quarried and spread over fields of vegetables and grapes and serves as an excellent evaporation suppressant (FIGURE 50).

Paper and Plastic Mulches

Paper and polyethylene plastic mulches are now widely used to control weeds, increase soil temperature, and speed up plant germination and growth. Their use specifically to retard evaporation in arid regions is now being researched (FIGURES 51 and 52). Yields of irrigated corn per unit of water evaporated and transpired have been nearly doubled in one experiment where the soil was covered with plastic film, indicating that up to half the water used by unmulched corn may be lost through evaporation from the soil surface.[39]

Latex, Asphalt, or Oil Mulches

Latex, asphalt, and oil have been tested in specific desert situations for their ability to conserve soil moisture, to concentrate rainfall (by creating runoff), and to suppress the movement of wind-driven sand long enough for plants to get established.

These mulches have been used commercially to establish vegetation on water-bearing sand dunes in, for example, Libya, India, and Australia (FIGURES 53-55). By retaining the heat absorbed during the day, they can keep desert soils warm during cool nights. This increases the chances of survival for plants whose roots must otherwise withstand large daily temperature fluctuations.

Other Chemicals

Silicones, polyethylene oxides, polysaccharide gum mixtures, fatty alcohols, and cationic, anionic, and nonionic chemicals have been tested as evaporation suppressants without much success.

[39] Doss, et al. 1970. (See Selected Readings.)

FIGURE 50 Cinder mulch on Lanzarotte, Canary Islands. After volcanic eruptions in the 1700s covered fields with cinder, many plants throve. Cinder preserves moisture during the rainless months. Semicircular stone-and-cinder walls add wind protection for this vineyard. (Flip Schulke, Black Star, (c) National Geographic Society)

FIGURE 51 A biodegradable, plastic-coated paper mulch. In experiments, cantaloupe yields increased by 123 percent, the total number of melons was doubled, and their diameter was increased by approximately 0.5 in. The percentage of marketable fruits and the total of soluble solids per fruit remained unchanged. (W. N. Lipe)

Advantages

The major advantages of mulches are that they conserve moisture, reduce wind and water erosion, and increase crop yields, especially in dry years. Mulches that increase soil temperature (plastics, asphalt, oil, dark-colored gravels and rocks) hasten germination and seedling growth in regions where soils are cold at planting time. Mulches can improve the quality of some fruits by preventing their contact with the soil. Plastic and petroleum mulches can be used to collect runoff water in depressions around plants, making a form of runoff agriculture (FIGURE 52).

Limitations

For most mulches, the prime limitation is cost. Treating soil with chemicals or covering it with plastic sheets is not cheap. Today, these treatments are suitable only for intensive agriculture of high-income crops such as pineapple and strawberries, or where a complementary feature such as stabilizing sand dunes adds significant economic benefits. The costs of

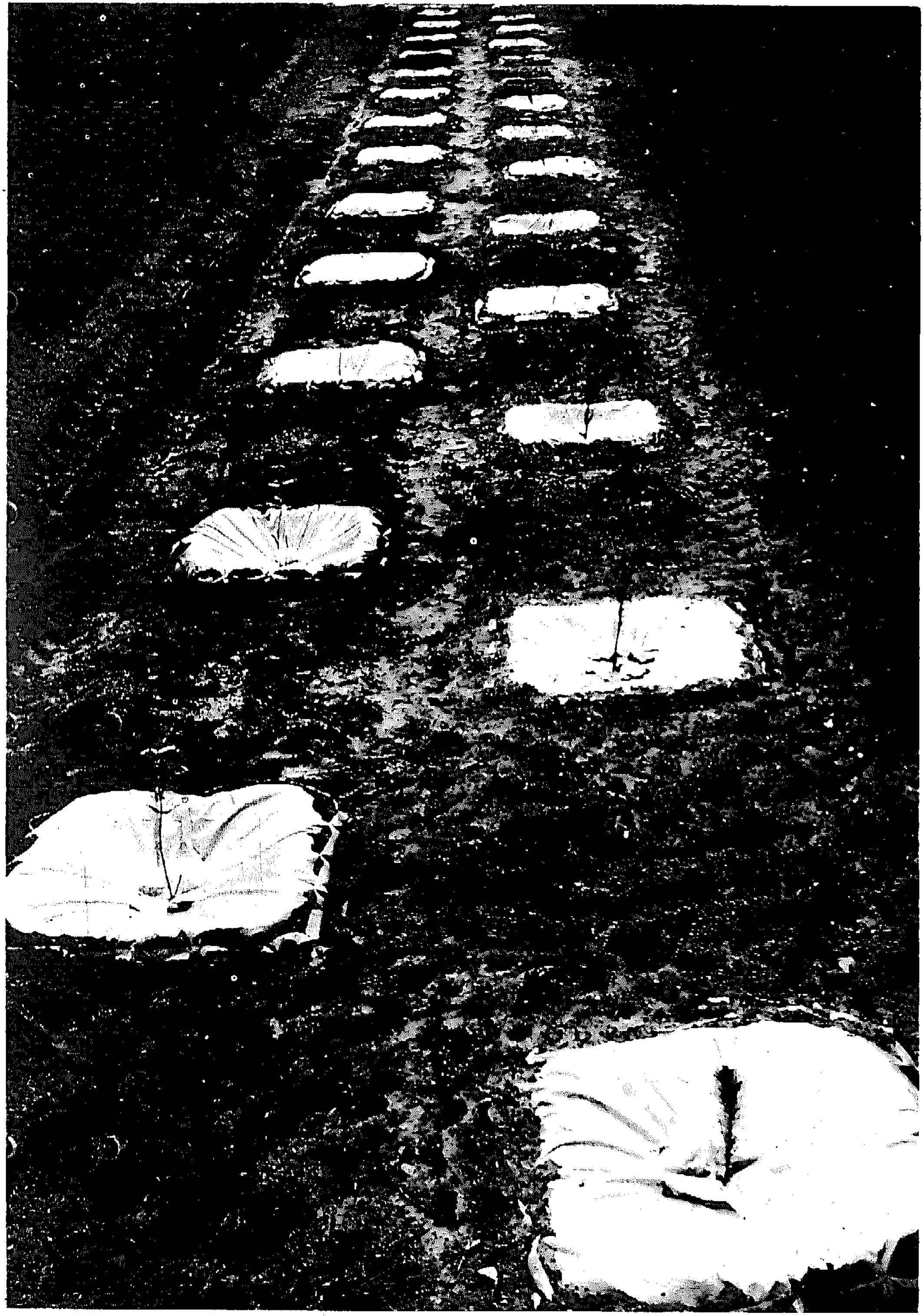

FIGURE 52 These plastic "aprons" are being evaluated to determine their ability to catch rainfall (chapter 2), reduce evaporation, suppress weeds, and promote the growth of tree seedlings in arid areas. (FAO)

FIGURE 53 Stabilizing dunes with a heavy oil mulch in the Rajasthan Desert, India. This process was first applied in Libya to 160 ha of bleak, barren stretches of the Sahara Desert (see also FIGURE 55). The dunes contained moisture 0.5 m below the surface. After treatment they were planted with 60,000 eucalyptus trees; 90 percent survived the planting and continued to grow. One m high when planted, they grew to over 2 m during the first year. Unstabilized sand would either bury the young plants or blow away, exposing their roots. (Exxon)

chemical and plastic mulching may also be justified in locations where soil erosion can be inhibited. Prices are affected by

- Availability of ingredients (e.g., latex, oil, water);
- Topography of the area to be treated, its fertilizer needs, and the amount of preparation, such as leveling, required;
- Availability of suitable machinery and personnel for both preparing and treating the area; and
- Type of vegetation to be planted.

The main disadvantage of plant residues as mulches is their relatively short lifetime. They are also difficult to keep in place in windy weather. Plastics, on

FIGURE 54 Consistency of sand stabilized with an oil/latex mulch. Sealed surface reduces evaporation losses and holds the sand in place long enough for plants to become established. (International Synthetic Rubber Company, Ltd.)

the other hand, deteriorate slowly and may interfere with the planting of subsequent crops. Gravel and rock mulches are not moved by wind, and they allow rainfall penetration. But they may be expensive to install and can interfere with tillage operations.

Stage of Development

Mulching with rock, gravel, and crop residues are age-old methods for conserving soil moisture; nevertheless, their worldwide potential today is not fully appreciated. Minimum-tillage agriculture has only recently been widely appreciated as a desirable agricultural practice. The nonporous mulches—plastic, paper, oil, asphalt, and latex—have all been made possible by

FIGURE 55 Two years after treatment as in FIGURE 54, eucalyptus trees, 0.5 m tall when planted, have grown to 1.5-3 m. In the Libyan desert mulches protect thousands of hectares of freshly planted young trees from encroaching sand. (International Synthetic Rubber Company, Ltd.)

technological developments of the last decade or so. Large-scale field trials are now beginning to demonstrate their worth.

Needed Research and Development

The main need is to develop mulches specifically for arid developing countries, particularly mulches that maximize the use of local resources. Arid-land studies on the following are also needed:

Thickness of mulches
Potential toxicity to plants and soil organisms
Alterations of the microenvironment by tillage operations
Improvement of equipment to generate and maintain gravel mulch

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Contacts

Agricultural and Irrigation Engineering Department, Utah State University, Logan, Utah 84321, USA (R. J. Hanks)

Agriculture Division, ARAMCO, Dhahran, Saudi Arabia (S. Labban)

Department of Agronomy, College of Agricultural Sciences, Texas Tech University, Lubbock, Texas 79409, USA (H. E. Dregne)

Department of Horticulture, University of Illinois, Urbana, Illinois 61801, USA (H. J. Hopen)

Department of Horticulture and Landscape Architecture, University of Arizona, Tucson, Arizona 85721, USA (N. R. Oebker)

Great Plains Field Station, U.S. Department of Agriculture, Agricultural Research Service, Mandan, North Dakota 58554, USA (W. Willis)

Ministry of Agriculture, Tripoli, Libya (M. Thahny)

U.S. Department of Agriculture, Southwestern Great Plains Research Center, Agricultural Research Service, Bushland, Texas 79012, USA (B. D. Stewart)

Water Resources and Development Service, Land and Water Development Division, Food and Agriculture Organization of the United Nations, Via delle Terme di Caracalla, 00100, Rome, Italy

10 Trickle Irrigation

Standard irrigation methods are particularly wasteful of water in arid lands because the extended areas of wetted soil greatly encourage evaporation (chapter 9). A newly developed irrigation system, known as "drip" or "trickle" irrigation, uses a system of plastic pipes placed among the plants on or under the soil (FIGURES 56, 57). Water carried in the pipes drips onto the soil through outlets arranged near each plant (FIGURE 58); because only a small amount of soil is watered, evaporation losses are minimized. Furthermore, the rate and time of water application are adjusted for no runoff and minimal deep percolation losses.

Trickle irrigation is potentially important for many irrigated crops in arid lands. It is already used extensively on tree, vine, and row crops, but because of high costs it is not yet used much for field crops. It has particular promise for slopes or rocky areas where land leveling for conventional irrigation is prohibitively expensive.

FIGURE 56 Trickle irrigation, showing the areas wetted by individual drippers attached to the plastic pipes. (S. Davis)

FIGURE 57 Trickle irrigation system in California, USA. Pipes lead the water to emitters beside the trees. (F. K. Aljibury)

FIGURE 58 Trickle emitter dripping irrigation water. (F. K. Aljibury)

Method

In trickle irrigation small amounts of water are applied at frequent intervals to a specific site near each plant. Under each site a wet area is formed, that extends to the plant's roots. The application can be adjusted to replace water continually as it is used up by the plant. To conserve energy and minimize flow rates, trickle-irrigation systems are normally operated at relatively low pressures (1–3 atmospheres).

Basic equipment for trickle irrigation consists of a water-supply head, a main, delivery pipes, manifolds, lateral hose lines, and emitters. The head, between the main water source and the pipeline network, usually consists of control valves, couplings, filters, screws, timeclocks, fertilizer injectors, gauges, etc. Since the water passes through very small outlets in the emitters, it is screened, filtered, or both before it is distributed in the pipe system.

Advantages

Trickle irrigation is replacing surface irrigation in some areas where:

- Water is scarce or expensive,
- The soil is too porous or too impervious for gravity (flood or furrow) irrigation,
- Land leveling is impossible or very costly,
- Water quality is poor,
- It is too windy for sprinkle irrigation,
- Trained irrigation labor is not available, or
- Irrigation labor is expensive.

Trickle irrigation not only improves the efficiency of water use but also gives much greater control over the placement and amount of water. The amount of water can be adjusted to the soil's absorptive capacity and to the characteristics of the particular crop, its stage of growth, and the climatic conditions. Thus, unlike other irrigation methods, trickle irrigation minimizes surface standing water, which can breed mosquitoes and increase waterlogging and anaerobic soil conditions that adversely affect plant growth.

Trickle-irrigation equipment costs must be judged in light of the expensive land preparation (and continued land maintenance) often required by surface irrigation. Land leveling, and canal and drain digging, require heavy equipment, skilled operators, and a considerable infrastructure; all are dispensed with in a trickle-irrigation system. The potential cost savings are large.

Fertilizers can be applied through the trickle system and efficiently applied close to the roots. Fertilizing through the trickle system generally promotes better plant growth response; the timing and number of applications required, however, are still uncertain and under study.

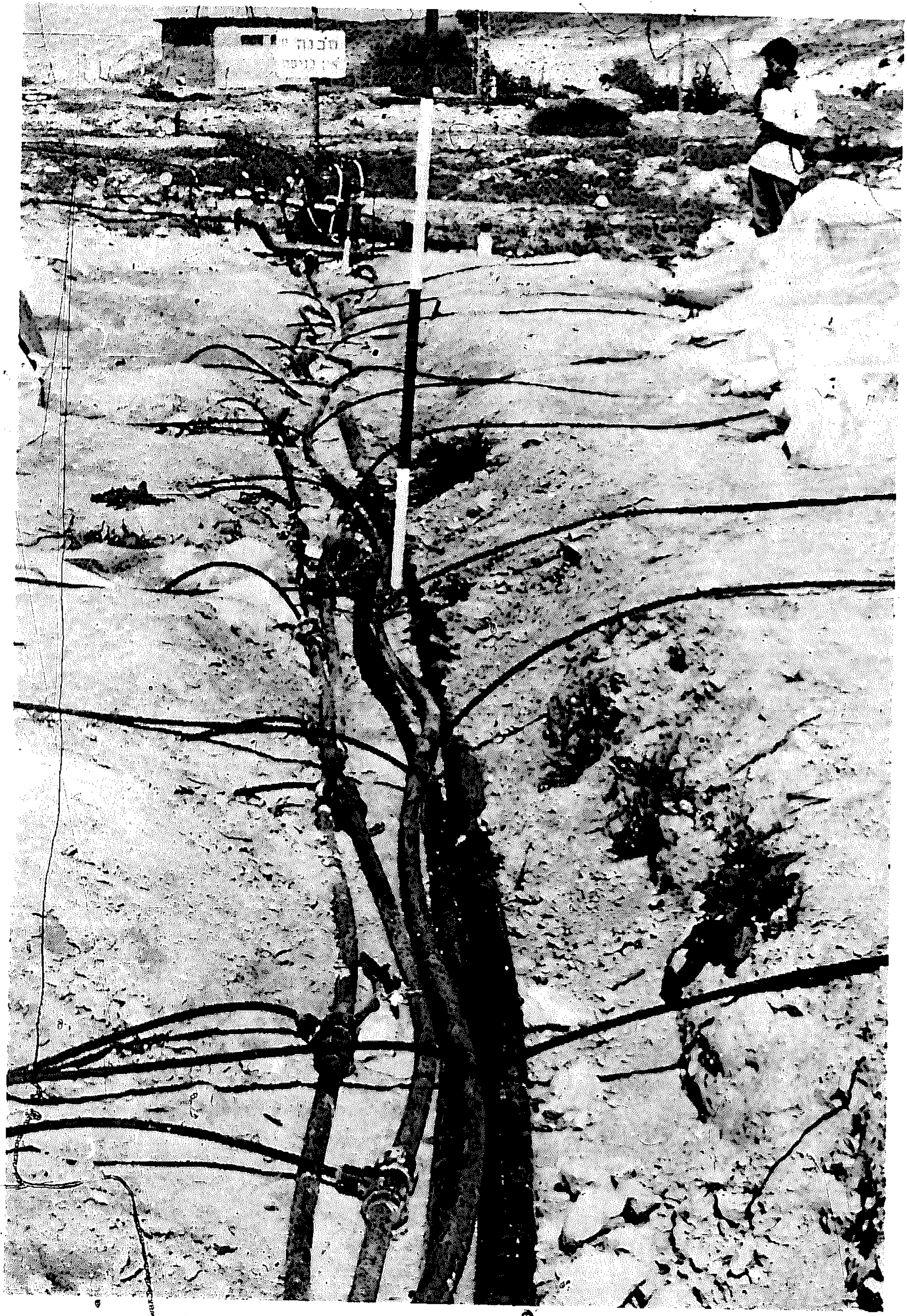

FIGURE 59 Plastic pipes for trickle irrigation, using water from a brackish geothermal aquifer, Mashabei S'deh, Israel. Unlike other irrigation methods, this one can easily keep the water warm with insulated pipes. Warm water heats the soil, stimulating plant growth by relieving the coldness of the desert night. (J. Schecter)

Because the irrigation water never touches the leaves, foliar salt damage is not a hazard with trickle irrigation. Provided the mechanisms of water and salt distribution in the soil are adequate, trickle irrigation may be a suitable way to use poor-quality irrigation water (e.g., saline waters up to 2,500 mg of salt per l; see chapter 3 and FIGURE 59).

Many moisture-induced leaf and stem diseases (e.g., fungal diseases) fostered by other methods of irrigation are minimized or defeated by trickle irrigation, which may also help control pathogens that develop in waterlogged soils.

Because trickle-irrigation water drips onto the soil without disturbing the surface, soil erosion and surface crustation, which impede water penetration, are usually eliminated.

Limitations

To design, install, and operate a trickle-irrigation system, skills different from those for other systems are needed. Potential users, unfamiliar with the technology, are urged to consult with specialists to identify the best design for their area. Unfortunately, numerous unproved claims for such systems have been made by aggressive promoters; all claims should be carefully studied and analyzed.

Trickle irrigation has proved most effective for permanent tree and vine crops, and for crops grown totally under cover (chapter 15). In many standard situations, however, it may be less appropriate than conventional methods.

There are some serious technical problems with trickle irrigation. The primary problem is clogging of the emitters by:

Precipitates from limestone-containing waters
Precipitates from iron-containing waters
Algae
Suspended silt, clay, or fine sand

Some clogging problems can be eliminated by careful management, filtration, and chemical treatment, but this increases operating costs. At present, trickle irrigation cannot be used with iron-containing water. Algae are normally removed by chemical treatment followed by filtration. Methods for removing fine sand, silt, and clay are still inadequate, especially where large amounts of suspended material are encountered. In addition, careful control during construction and maintenance operations is essential, to stop particles entering the system.

With trickle irrigation as with other methods, careful management and expert advice are essential when saline waters are used. This is especially true in arid areas because evaporation can cause surface accumulations of salts that damage crops when rains wash them down into the root zone. Furthermore, insufficient water for leaching (chapter 3) can result in salt buildup deep in the root zone. Although the salinization hazards of trickle irrigation remain to be quantified, they seem to be less than with other irrigation methods.

Trickle irrigation requires precise equipment which, though available, has not undergone long-term application. Particularly important in this respect are the emitters and filtration systems.

Stage of Development

The commercial use of trickle irrigation is rapidly increasing. An estimated 15,000 ha are under trickle irrigation in Europe, with an increase of 25 percent or more each year. California's trickle-irrigation acreage was 60 ha in 1970, 600 ha in 1971, 8,000 ha in 1972, and approximately 16,000 ha in 1973. It is used mainly for permanent crops such as avocados, strawberries, tomatoes (FIGURE 60), citrus, nut trees, and fine-wine grapes, grown either

FIGURE 60 Trickle-irrigated tomatoes on a 500-ha vegetable and fruit farm near Dakar, Senegal. Although high, the cost is offset by an estimated 30-40 percent savings in water over other irrigation methods, fewer weeds (saving time and labor), easier disease control, and easier access between rows. Fertilizers are injected into the trickle system, saving much of the usual application expense. (Bud Senegal)

in soils where water penetration is very slow or in highly porous soils where it is very high.

Development of trickle irrigation lags far behind that of other irrigation methods, including sprinkler irrigation. Although it is considered a new method, the basic concepts of trickle irrigation have been used since the early 1900s by nurseries growing fruit trees and ornamental plants.

Needed Research and Development

Fairly good filters are available, but improvements in design are needed to reduce or alleviate the problem of emitter plugging. Self-cleaning emitters have been devised but not yet proved in long-term use. The problem is to devise low-cost, low-maintenance filters than can remove extremely fine precipitates, sand, clay, silt, and algae particles. As yet, no filter screen or separator device can meet the desired service requirements.

Other needed technical developments include:

- Cheaper and stronger emitters;
- Simple, reliable hoses and connections, especially ones that rodents cannot chew;
- Devices and systems for reliable low-cost automation, particularly moisture sensors for determining when irrigation is needed; and
- Suitable pressure- or flow-regulating devices to offset pressure variations due to topography or pipe friction that cause different drip rates throughout the system.

Much still remains to be learned about trickle irrigation and its effects on crops in the field. Widespread field tests of the trickle method are needed on:

- Crop response in a variety of soils, crops, and climates;
- The movement of water and solutes in the soil;
- The effects of applying fertilizer via the trickle-irrigation system;
- The influence of trickle irrigation on specific plant diseases and pests;
- The feasibility of protecting plants by delivering herbicides, algicides, nematocides, fungicides, etc., through the trickle system; and
- The salinization hazards of trickle irrigation.

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Contacts

Many companies around the world are now beginning to market equipment for trickle irrigation. Local departments of agriculture or agricultural extension services should have pertinent information. The following are monitoring research developments:

Agricultural and Irrigation Engineering Department, Utah State University, Logan, Utah 84321, USA (J. F. Alfaro and J. Keller)
Agricultural Engineering Department, Technion, Haifa, Israel (D. Karmeli)
Agricultural Extension Service, San Diego County, Bldg. 4, 5555 Overland Avenue, San Diego, California 92123, USA (C. D. Gustafson)
Agricultural Extension Service, University of California at Riverside, Riverside, California 92502, USA (A. W. Marsh)
Department of Soil, Water, and Engineering, University of Arizona, Tucson, Arizona 85721, USA (D. D. Fangmeyer)
Polytechnisches Institut, 75 Karlsruhe 1, Postfach 6168, Germany (Dr.-Ing. W. Ständer)
Soil and Water Laboratory, Irrigation Department, Yotvata, Arava Desert, Israel (M. Shmueli)
Soils and Agricultural Engineering Department, U.S. Department of Agriculture, Agricultural Research Service, University of California, Riverside, California 92502, USA (S. Davis)
Water Resources and Development Service, Land and Water Development Division, FAO, Via delle Terme di Caracalla, 00100, Rome, Italy

11 Other Innovative Irrigation Methods

Besides trickle irrigation (chapter 10), interesting innovations include special methods of sprinkle irrigation and subsurface irrigation. Examples are illustrated in FIGURES 61-68.

FIGURE 61 Gated pipe delivering water in metered quantities from farm turnout or tube well to a series of furrows (or a border). Pipe is available in plastic (lay-flat or rigid), aluminum, or other lightweight, portable materials. Pipelines take the place of field ditches and can convey water across uneven terrain, reducing the need for land leveling. They also eliminate ditch losses, which results in considerable savings in water. (U.S. National Water Commission)

FIGURE 62 Fixed-orifice sprayer irrigation in an orchard. Similar to trickle irrigation in concept and design, it requires less filtering. Evaporation losses are higher; winds cause the spray to drift, leaving dry areas. The larger areas of wetted soil may increase weed problems, and foliar damage may result where low-quality (e.g., saline) water is used. (J. Keller)

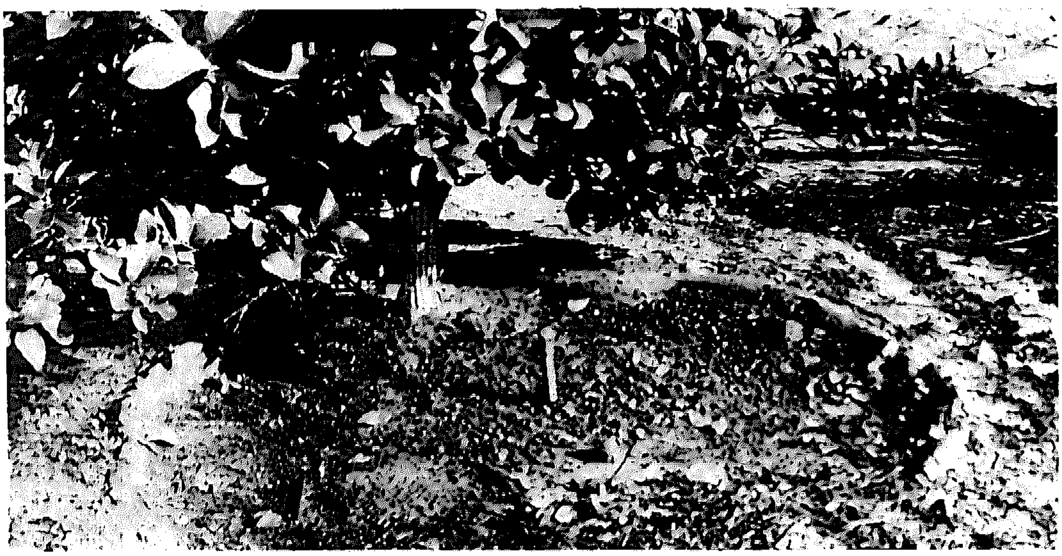

FIGURE 63 Spitters and bubblers are used to irrigate citrus in parts of the southwestern United States. The bubbler shown here delivers water to a basin designed to retain the water close to the trees. Water that requires little or no filtration is pumped through underground plastic pipelines to reduce water-conveyance losses and is discharged as a small spray near the tree. The basin method allows irrigation on slopes and uneven terrain. (USDA Soil Conservation Service)

FIGURE 64 Center-pivot sprinkler irrigation system at Kufra, Libya, deep in the Sahara Desert. Water mined from a subterranean aquifer through a well at the pivot point has produced 4 crops of wheat and barley and 12 of alfalfa per year from land that never before supported plant life. The center pivot is the simplest fully automatic irrigation system. A rigid pipe up to 500 m long is suspended above the crop on wheeled carriages. The pipe is rotated around the pivot point by hydraulic or electric motors at each carriage. Capable of providing high-quality irrigation with a minimum of operator experience, this irrigation system is best adapted to high-intake-rate soils requiring frequent irrigation. (D. Bayes)

FIGURE 65 Perforated pipe operating at about 1 atmosphere pressure is a suitable irrigation system for soils that take in water rapidly. The aluminum or plastic pipes are easily movable and can be supplied from low-pressure mainlines. The plastic pipe in this example is collapsible (lay-flat) and can be easily rolled up. Gravity pressure is often sufficient, so pumps are unnecessary. Little or no land shaping is needed, and, as shown in this picture, the method can be used on sloping terrain. A relatively clean water supply or system is required. (Rhodesia Journal of Agriculture)

FIGURE 66 Wet spots from subsurface irrigation. This mainly experimental technique employs the concepts of trickle irrigation, but the pipes are buried in the soil, and the water is released at the crop root level. The water supply is controlled so that as little water as possible reaches the soil surface. On the dry surface evaporation is reduced, which saves water, decreases salinization of the soil, and also allows the use of more saline water (the salt-concentrating effect of evaporation is reduced.) Like trickle irrigation, this system is subject to orifice blockage, but because the water is released below the ground it may not be noticed until it is too late to save the plant. (S. Davis).

FIGURE 67 Subirrigation in the San Luis Valley, Colorada, USA. As in FIGURE 66, this method irrigates the root zone without wetting the soil surface, but it also artificially raises the whole water table into the root zone. In practice, the water table is supplied from border ditches. Small barriers are used to raise the water level in the ditch; capillary action raises the water table throughout the field. Because the water supply comes up from below the root zone, very little reaches the soil surface; this decreases evaporation, salinization, and weed germination. (USDA Soil Conservation Service)

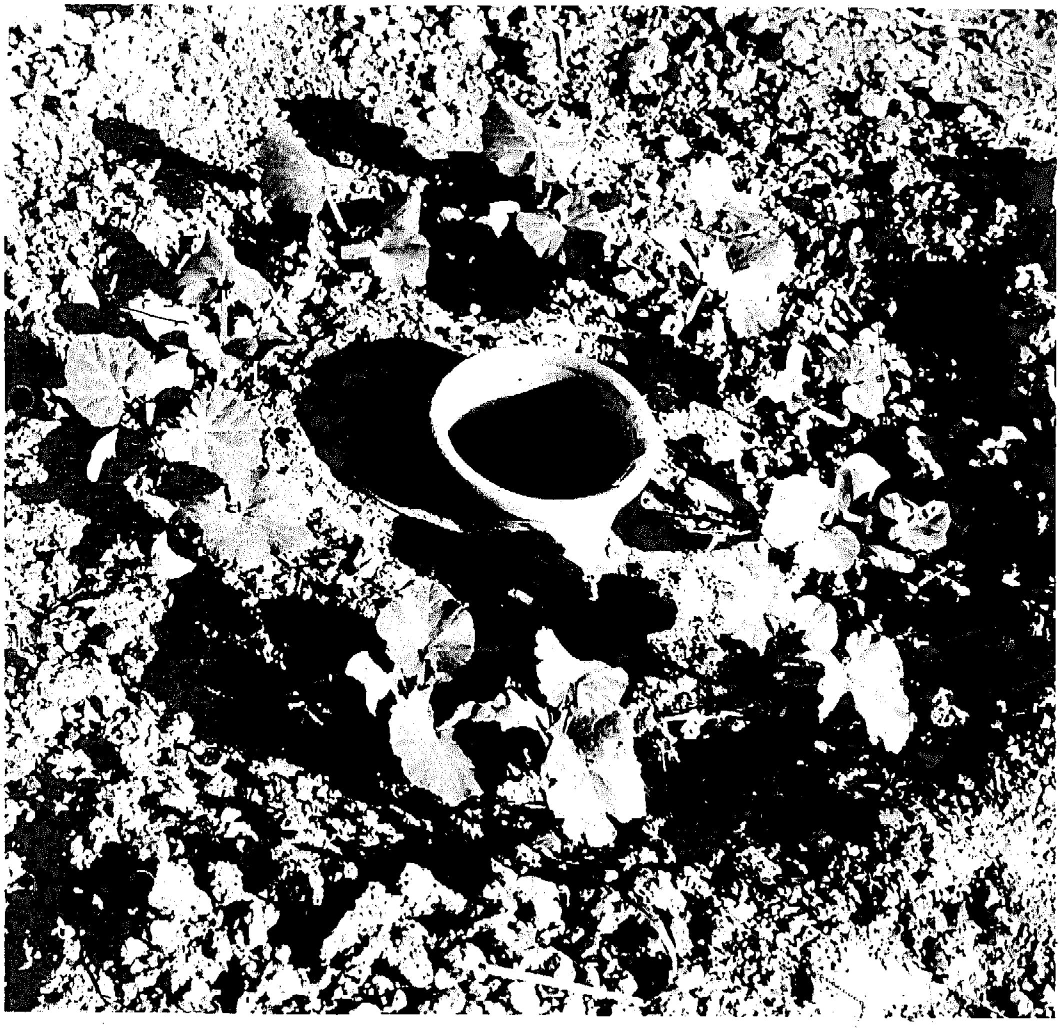

FIGURE 68 Pitcher irrigation, a new development, uses unglazed baked earthern pitchers, which are widely available and very cheap in many developing countries. The pitcher is buried to its neck in the soil and filled with clean water. Vegetable seeds are planted around it. Enough water soaks through the porous pitcher into the root zone to maintain plant growth. Experiments in India have grown melons and pumpkins to maturity with very little water (less than 2 cm/ha for the entire 88-day growing period). Very little evaporation occurred because there was no standing or surface water. (Picture and information supplied by R. C. Mondal, Central Soil Salinity Research Institute, Karnal, Punjab, India)

12 Reducing Cropland Percolation Losses

Of the many kinds of agricultural soils, sand is one of the most challenging. Millions of tillable hectares of sandy soils, widely distributed throughout arid regions, are seldom used for agriculture because of their low productivity. Frequently, this low productivity is due to an inability to prevent water from percolating away too rapidly for plant growth. Growing crops in sandy soils thus requires frequent irrigation; in many arid regions this is not practical, particularly if rainfall provides the only water.

Techniques have been developed to produce artificial underground moisture barriers that keep water and nutrients from percolating below the root zone. A properly engineered artificial moisture barrier can overcome many of the hydrological disadvantages of sandy soils. By retaining more water in the root zone, it can create a soil suited to crop production (see FIGURE 69).

Moisture barriers occur naturally in some deserts where, for example, sand overlies a less pervious loess soil and are often revealed by luxuriant growths of wild vegetation.

Method

Underground moisture barriers are continuous films of a water-resistant material placed approximately 60 cm below the soil surface with gaps every 150 m or so for drainage.

Although most barriers have been made of asphalt, any durable water-impervious material can, in theory, be used. Plastic sheets have been used for this purpose in East Africa[40]; layers of compost or manure rich in colloids have been used in Hungary.[41]

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[40] Gerakis and Tsangarakis. 1970. (See Selected Readings.)

[41] Egerszegi. 1964. (See Selected Readings.)

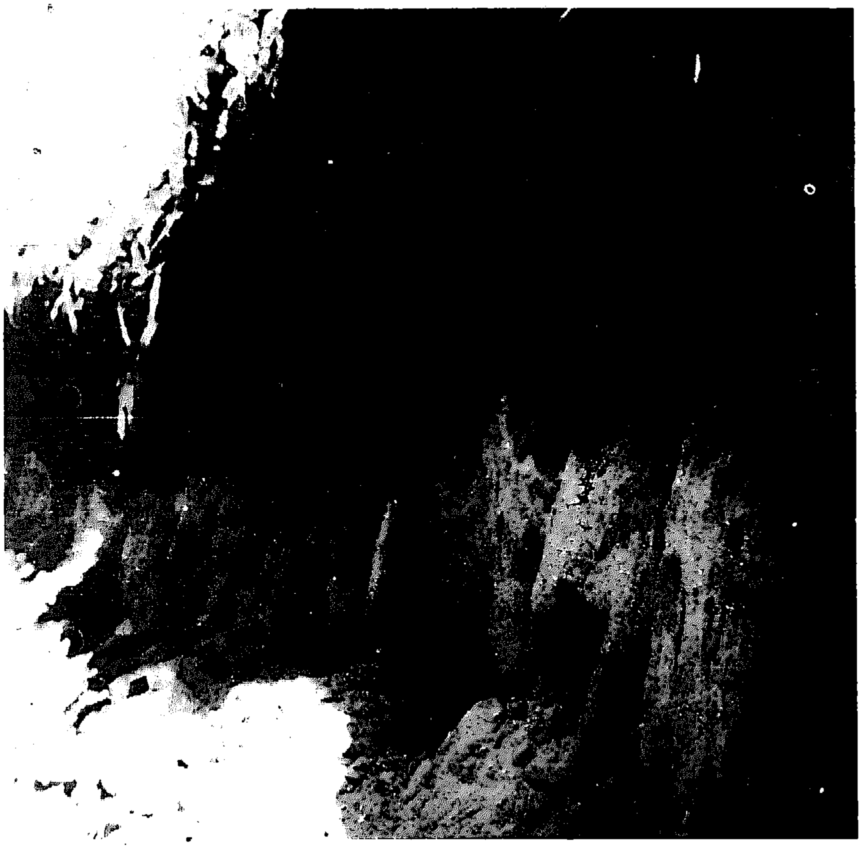

FIGURE 69 Retention of water above an asphalt barrier 24 inches (60 cm) deep in fine sand. (A. E. Erickson)

The optimum depth for the barrier depends on the moisture-holding characteristics of the sand. The extent of the barrier is determined by drainage considerations.

One way to install a barrier is to remove the topsoil, hand-place the moisture barrier, and then refill the area. But machines have been built that will install a waterproof asphalt barrier without excavation. A wide, wedge-shaped plow pulled through the ground (50–70 cm below the surface) lifts the soil and nozzles spray asphalt into the cavity. The asphalt immediately hardens into a moisture-proof layer 2–3 mm thick before the earth falls back in place.[42]

Advantages

Unlike many other soils, sand has a surface durable enough to withstand the abuses of tillage and farming; it allows quick intake of rainfall or

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[42] Erickson. 1972. (See Selected Readings.)

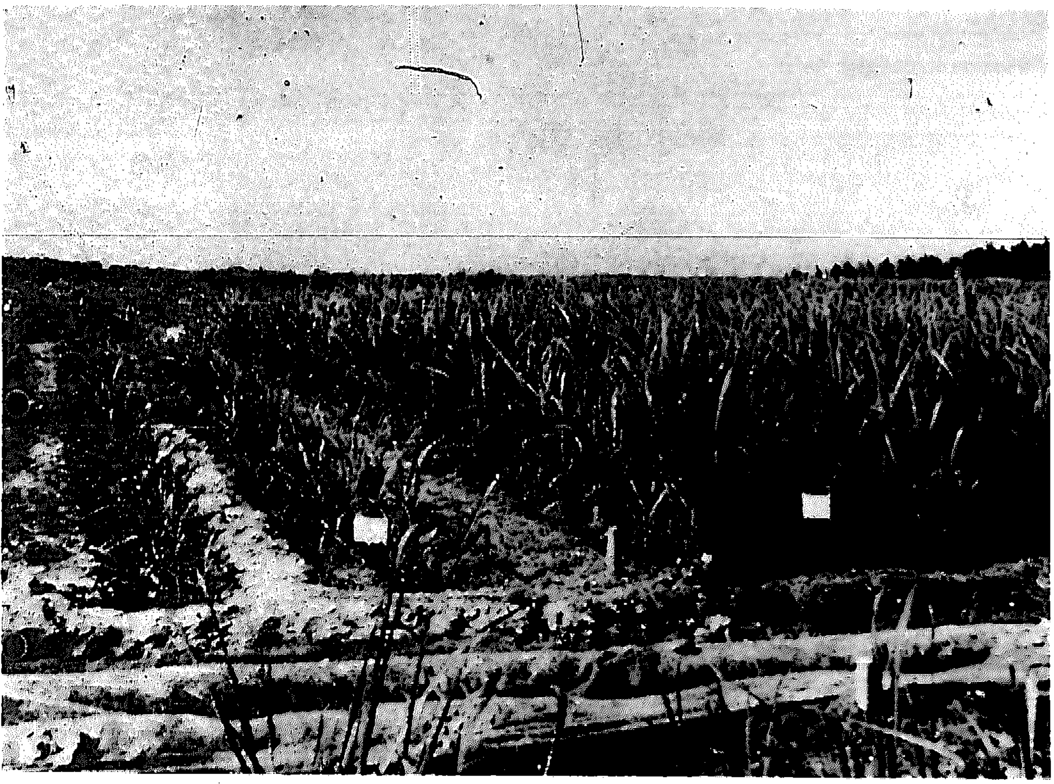

FIGURE 70 Spring-planted, furrow-irrigated sugarcane growing on a fine-sand soil in Taiwan. Cane to the right of the stake is growing over a moisture barrier. After 1 year the cane on the barrier yielded 104 MT/ha compared to 54.2 on the control. The barriered soil required only 90 mm of irrigation, while the control needed 281 mm. (A. E. Erickson)

irrigation water; its good capacity for aeration favors root development; and its upper layers often serve as a mulch, reducing losses from evaporation (chapter 9). When its low capacity for retaining water is corrected, sand can become highly productive.

A barrier gives sandy soil a storage capacity equivalent to that of a better agricultural soil in a temperate region. Thus, barriered soils require less frequent irrigation than unbarriered soils and can save 50-75 percent of irrigation water.[42] Barriers also allow furrow or border irrigation on sandy soils that otherwise could not be efficiently irrigated by these methods. In a tidal area in Taiwan, an experiment has demonstrated the use of barriers for restricting the upward movement of salt into the root zone.[43]

Sandy soils with barriers can produce crop yields equivalent to those of the best soils in their areas and much higher than those obtainable from the original sand soil. (See FIGURE 70.) Yield differences between barriered and

[42] Erickson. 1972. (See Selected Readings.)
[43] Wang, et al. 1969. (See Selected Readings.)

nonbarriered soils generally depend on the amount of drought during a particular season.

Field studies have shown that barriers prevent fertilizer, as well as water, from sinking below the root zone.

In many ways subsurface moisture barriers bring advantages similar to those of trickle irrigation (chapter 10) to sand soils. The preferred method for a given site will depend on such matters as the crops to be grown, the quality of the water, economics, and the operators' preference.

Limitations

Today, the cost of underground moisture barriers is high—largely due to the cost of the barrier material. To install a barrier in the United States using the mechanized system costs $625-$750/ha; thus, it can be used only where agricultural production on marginal land is desperately needed, where the soil is otherwise useless, where high-value crops can be grown, or where water is in short supply.

Deep roots penetrate moisture barriers but do not continue growing in the water-deficient soil below them. Crops with deep roots, especially tap roots, could, however, eventually perforate the barriers and reduce their efficiency.

The biggest technical problem in producing a moisture barrier is to seal the joints between successive strips. This is particularly so in barriers laid by mechanized systems.

The question of whether salinity builds up in the soil because drainage is retarded by an underground moisture barrier is not completely answerable today. Since no barrier yet built has been completely watertight, drainage has leached the salts away (chapter 3) and kept them within acceptable levels. In some cases, however, a certain amount of irrigation water must be reserved solely for leaching.

Stage of Development

Underground moisture barriers have been developed to the point at which researchers believe they are ready for commercial application. Field experiments have been conducted with vegetables and field crops, with and without irrigation, in Egypt, South Africa, and Swaziland; in wet and dry regions of the United States; and with rice and sugarcane in Taiwan.

Under present conditions underground moisture barriers are economically feasible in many areas of the world, but only for high-profit crops. With man's increasing need for additional land and water, this technique may prove increasingly valuable as a way to produce more food on otherwise unproductive sandy soils.

Needed Research and Development

Further effort is needed to reduce costs, perhaps through development of new, cheaper materials.

No serious danger of salinity buildup is anticipated with good water management, but further research is needed to settle this point.

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Contacts

AMOCO, Moisture Barrier Co., 200 East Randolph Drive, Chicago, Illinois 60601, USA. (W. O. Frazier)

Arizona Agricultural Experiment Station, Yuma, Arizona 85364, USA. (B. Gardner)

Crop and Soil Science Department, Michigan State University, East Lansing, Michigan 48824, USA. (A. E. Erickson)

Department of Agricultural Engineering, Indian Institute of Technology, Kharagpur, West Bengal, India.

Department of Agronomy, University of Florida, Gainesville, Florida 32601, USA. (L. C. Hammond)

Department of Soil Science, University of Natal, Pietermaritzburg, South Africa. (M. E. Summer)

Research Institute of Soil Science and Agricultural Chemistry of the Hungarian Academy of Science, Budapest, Hungary. (S. Egerszegi)

Taiwan Sugar Experiment Station, Tainan, Taiwan. (C. C. Wang)

13 Reducing Transpiration

Only 1 percent of the water absorbed by roots is encorporated into the plant cells; 99 percent moves up through the plant and passes into the atmosphere as water vapor. This process, called transpiration, differs from evaporation in that it takes place on living tissue and is influenced by the physiology of the plant. One ha of growing vegetation can transpire as much as 94,000 l of water per day. If a practical way to reduce transpiration could be found, substantial reductions in water demand could be achieved, especially in arid lands.

Methods

Transpiration losses can be reduced in the following ways:

- Destroying unwanted phreatophytes—plants that transpire efficiently. Phreatophytes, such as salt cedar and mesquite, often have roots that penetrate groundwaters at great depth. The groundwater losses they cause are not widely recognized, but in the semiarid western United States it has been estimated that phreatophytes covering 6 million ha cause a total loss of over 25 billion m^3 of water each year.[44]
- Breeding plant varieties that transpire less (chapter 14).
- Enclosing crops within a structure (chapter 15) so that transpired water can be collected and reused or so that the humidity rises and retards the transpiration process.
- Reducing air movement over a crop by, for example, windbreaks of interplanted rows of taller plants.
- Removing unproductive leaves physically or with defoliants. In crops such as wheat and barley, upper leaves contribute most to the developing grain. Removing the lower leaves, if properly timed, can reduce water lost by transpiration with little or no loss in grain yield.
- Using chemical antitranspirants.

[44] Robinson. 1952. (See Selected Readings.)

Transpired water is passed out of the plant through stomata—pores in the leaf surface through which carbon dioxide, oxygen, and water pass. Chemical antitranspirants are sprayed onto the stomata-bearing surfaces of the leaves (usually, stomata are concentrated on the undersurfaces) to inhibit water passage. Although the technology is embryonic, present antitranspirants have reduced water losses by 40 percent in some experiments (FIGURE 71). The frequency of spraying depends on the antitranspirant's durability and the rate at which new foliage is produced. Present evidence indicates that most antitranspirants may be effective 1–4 weeks, although some reductions in transpiration have been observed over several months.

Chemical antitranspirants work by

- Closing stomata;
- Forming a film over the stomata; or
- Cooling the leaf with a reflecting coat that reduces the amount of solar energy absorbed.

Stomata-closing Materials

The opening and closing of stomata are caused by two highly specialized guard cells surrounding the aperture. Several chemicals can prevent complete opening of the guard cells, thereby decreasing the loss of water vapor from the leaf. Most promising of these inhibitors are certain alkenylsuccinic acids and abscisic acid.

Film-forming Materials

Leaves can be covered with films that form transparent barriers to the escape of water vapor. Materials tried as antitranspirants include cetyl alcohol, silicones, wax, latex, and plastics. These film-forming materials reduce transpiration, but the yet unrealized ideal is one that is:

- Nontoxic to plants and animals;
- More permeable to carbon dioxide and oxygen than to water vapor, so that the plant's metabolism is not slowed;
- Highly permeable to the wavelenghts of light that most promote photosynthesis;
- Flexible enough to allow for leaf motion and expansion;
- Resistant to degradation by sunlight, microorganisms, and physical disruptions; and
- Economically attractive.

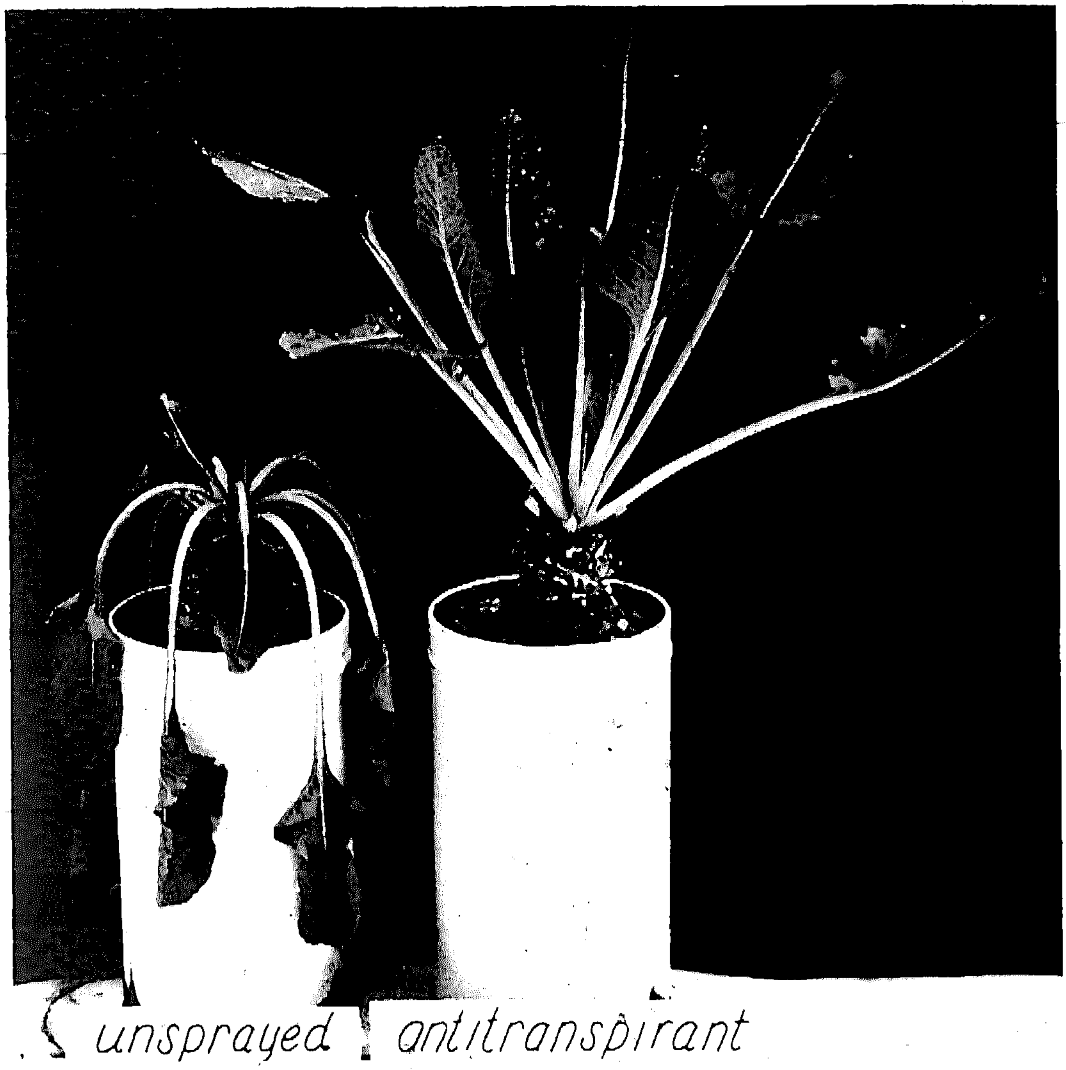

FIGURE 71 Matched sugarbeet plants, one treated with an antitranspirant, were irrigated to saturation and then allowed to grow without further water. Three days later the treated plant still retains its moisture and turgor; the other has wilted. (R. M. Hagan)

Reflecting Materials

Reflecting materials sprayed on leaves reduce the solar energy absorbed and lower leaf temperature and therefore slow down transpiration. Reflecting materials do not normally need to block stomatal pores on the undersurface of leaves; they interfere less with oxygen and carbon dioxide transfer than do the other chemical antitranspirants.

Advantages

Reducing transpiration reduces a crop's demand for water thereby allowing some crops to be grown in arid areas where the water supply is

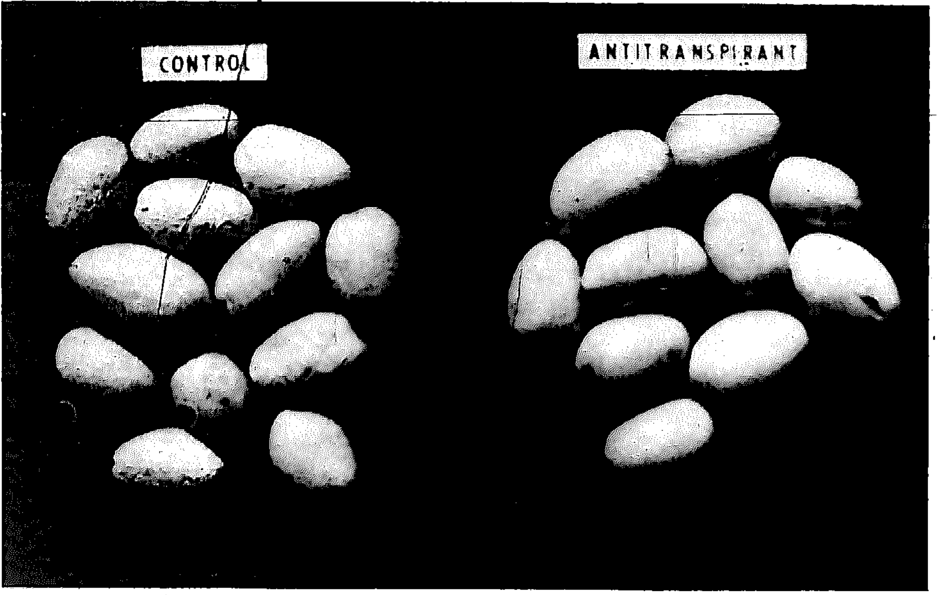

FIGURE 72 Preharvest antitranspirant spray reduces olive fruit shrivel: During an experiment in October 1971, California's severe drying winds shrivelled most of the fruit on untreated olive trees and only 15 percent were marketable, compared to 90 percent from antitranspirant-treated trees. (R. M. Hagan)

otherwise inadequate. Even a small reduction in transpiration results in a major water saving, because normally most of the water absorbed by a crop is transpired and because within the plant itself is the most efficient place to save water. Any saving at the plant is equivalent to a manyfold saving at earlier points because of losses in storage, conveyance, distribution, and field application in the irrigation system.

A modest reduction in transpiration has been shown to improve yields and quality of some flower and fruit crops because less moisture and juice are lost from the flowers and fruit (FIGURE 72).

Limitations

The limitations of reducing transpiration water losses either by breeding plants that transpire less or by enclosing plants within a structure are covered in chapters 14 and 15. Destroying phreatophytes is very controversial; it may disrupt the always-fragile arid environment.

Stomata serve as portals for the intake of carbon dioxide (necessary for photosynthesis and growth); thus, a chemical barrier against water loss may reduce plant growth if it also interferes with the passage of carbon dioxide. Today's chemical- and film-forming antitranspirants do restrict carbon dioxide movement and, thus, are most useful where water conservation is so important that maximum plant growth can be sacrificed, as in the cases of wild phreatophytes or plants for landscaping, lawns, and highway borders.

Some antitranspirants damage plant cells. Many stomata-closing materials, even when very dilute, are toxic to some plant species and should be used with care. Their effects on animal life have not yet been fully investigated.

One effect of normal transpiration is to cool the plant, and the film-forming and stomata-closing types of chemicals can adversely affect plant growth because they tend to increase leaf temperature slightly.

Present antitranspirants affect only the leaf surface to which they are applied and therefore are of little use on rapidly growing crops whose leaf surfaces are expanding rapidly.

Stage of Development

Transpiration reduction is mainly experimental today. Although great potential exists, basic research on antitranspirants has so far been meager and not overly encouraging for their widespread use. But antitranspirants can be used where retarded plant growth is acceptable.

During the early 1900s, nurserymen and foresters dipped seedlings in wax or wax-oil emulsions to prevent wilting, and thereby increased the survival rate of their transplants. More recently in the United States antitranspirants have been

- Experimentally sprayed on a forest to increase the watershed runoff;
- Applied to phreatophytes to curtail water loss from groundwater supplies;
- Sprayed on highway plantings where irrigation is expensive and hazardous;
- Used successfully to increase the size and yield of orchard fruits by spraying trees just before harvest, when the size depends more on moisture content than on vegetative growth; and
- Used to reduce winter desiccation of plants, especially where soils are frozen.

Reflectant materials have been tried on artichokes in Israel with considerable success: the percentage of cuttings that rooted increased greatly; vegetative growth was improved; and higher yields were obtained.

Needed Research and Development

Research and development should be directed to the following:

- Development of antitranspirants that will give a maximum reduction in transpiration and a minimum reduction in photosynthesis. Recent research has done much to help elucidate the mechanism of natural stomata control, but the interactions of all factors affecting stomatal movement require further researching.

- Determination of optimum concentrations and application methods.
- Investigation of the numerous potential uses for such materials.

Research is also needed to improve the delivery of antitranspirants to leaf surfaces, especially undersurfaces, that are difficult to cover. Ground and aerial spraying techniques developed for pesticides may be useful, and perhaps the use of electrostatically-charged-droplet spraying could improve underleaf coverage (the electrostatic repulsion between droplets spreads them over the leaf surfaces).

Research in transpiration reduction by using reflectants could be profitable.

Another research goal is to develop a systemic transpiration suppressant, one that is absorbed by the plant and moved *internally* to the stomata. This would ensure uniform leaf coverage and would protect even new leaf growth. This has not been achieved to date, although abscisic acid (a stomata-closing compound) in the vase water of cut flowers has been shown to reduce water loss from the leaves.

Chemical research is needed to synthesize analogues of abscisic acid and other inexpensive compounds that would permit widespread utilization of the stomata-closing method.

Research on using antitranspirants to reduce moisture stress during water-sensitive growth stages (e.g., transplanting or germination) would help to increase plant survival under arid conditions.

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Contacts

Agricultural Research and Education Center, University of Florida, P.O. Box 1088, Lake Alfred, Florida 33850, USA (L. G. Albrigo)

Agricultural Research Institute, Rayack, Lebanon (A. Abou-Khaled)

Agricultural Research Organization, The Volcani Center, P.O.B. 6 Bet Dagan, Israel (G. Stanhill)

Department of Botany, Hebrew University, Jerusalem, Israel (J. Gale)

Department of Chemical Engineering, University of Colorado, Boulder, Colorado 80302, USA (F. Keith and A. Taori)

Department of Forestry, University of Wisconsin, Madison, Wisconsin 53706, USA (T. T. Kozlowski)

Department of Water Science and Engineering, University of California at Davis, Davis, California 95616, USA (R. M. Hagan and D. C. Davenport)

Department of Watershed Management, University of Arizona, Tucson, Arizona 85721, USA (D. B. Thorud)

14. Selecting and Managing Crops To Use Water More Efficiently

Most crops grown under irrigation in arid regions were imported from more temperate regions where efficient water use is not required. Some may need over 2,000 kg of water to produce 1 kg of usable dry matter. Since little has been done on the selection and breeding of food, forage, and industrial crops specifically to use less water per unit of product, much research is needed in this area. At the same time, wise selection of cultural practices can do much to improve the efficiency of water use.[45]

Methods

Selecting Plants for Water-Use Efficiency

A breeding program aimed at developing cultivars (varieties) for agricultural use under arid conditions can be approached (1) by selecting wild plants that now survive in desert conditions and putting them to use as food or cash crops; or (2) by selecting individual water-efficient plants from varieties of already-domesticated crops such as barley, sunflower, melons, sorghum, pearl millet, and beans, and using them in breeding programs. Many of our present staple crops appear to have originated under arid or semiarid conditions, which suggests that appropriate genotypes should be available. Although native desert plants should not be ignored, the best candidates for highly useful plants with low water requirements seem to be already-domesticated ones.

Selection can often be based on visual observation of varieties surviving with a marginal water supply, but there are several characteristics that can be used as guides for selecting promising varieties. The following kinds of plants seem to offer promise:

- Plants that grow in cool seasons when evaporation rates are lower (e.g., lettuce).

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[45] Many other chapters in this report are relevant to this topic. This chapter deals with some specific subjects not dealt with elsewhere.

- Rapid-growing plants (but without greatly increased water requirements) that shorten the time in which water is lost by transpiration and evaporation.
- High-yielding plants that require no appreciable increase in water supply, for example, the short-strawed wheat varieties evolved in Mexico that give double or triple the yield of older wheat varieties without increasing water demand and can double or triple water-use efficiency.
- Plants with low transpiration losses (chapter 13). For example, agave and pineapple close their stomata during the day when evapotranspiration losses are greatest; they consume less water than do plants that open their stomata during the day. Selection or breeding of plants to increase daytime stomata closure could reduce water loss. An alternative is to select species with stomata placed, distributed, or structured to transpire less water. For example, plants with most of their stomata on the undersurfaces of the leaves generally transpire less than plants having stomates on both sides. Arrangement, size, and shape of individual leaves may also prove important. Plants with a tall, open leaf structure, ideally suited to absorbing the sun's heat, transpire water faster than plants with a lower, more compact leaf structure.
- Plants that can tolerate low-quality (e.g., saline) water (chapter 3).

Drought is unquestionably the most important environmental factor influencing the growth of plants in the arid regions of the world. The small amount of rain in arid lands is intermittent and unpredictable; any arid-land crop has to survive droughts. Various characteristics, such as deep, well-branched roots, can be used as selection guides for plants that are drought resistant, but the basic physiology of the drought-resistance process in plants is complex and little studied.

Managing Plants for Water-Use Efficiency

In arid lands water supply is often not the major factor in crop yield; sometimes the crop's environment is the leading cause of inefficiencies in water use. For example, insufficient fertilizer, insect control, or disease control; improper cultivation; and excess weeds all reduce the yield and thus reduce water-use efficiency. Crop management that increases production also increases water-use efficiency.

Cultivation practices must reflect the importance of helping the plant's root system to extract meager moisture from arid soils. Practices that increase the rooting volume of the soil will improve yields and water-use efficiency. On the other hand, practices that interfere with roots may have adverse effects in arid lands, even if they are successful in temperate climates.

Plant populations must be large enough to permit full use of the available moisture, yet not so large as to reduce yield. Because variable rainfall makes it difficult to prejudge the moisture that will be available during the growing season, the task of selecting optimum population size is difficult. Cultural practices that result in overgrazing also reduce water-use efficiency by restricting the depth and ramification of the grass roots. Part of the reduction in yield experienced on overgrazed ranges may be due to a lack of sufficient vegetation to hold the rain and snow that fall. Thus, pasture and range management practices that minimize runoff and maximize infiltration use available precipitation more efficiently.

Cultivating crops in rows on the contour increases the infiltration of rainfall and reduces water and soil losses. Thorough weed control in fallowing operations facilitates water storage by eliminating transpiration losses (chapter 13). Leaving crop residues as a mulch often conserves water by reducing runoff and increasing infiltration. The mulching also reduces evaporation losses (chapter 9).

The date a crop is planted influences water-use efficiency. Generally, the earliest safe planting date is best, because the plants can utilize accumulated winter moisture and take advantage of cooler weather and, thus, lower evapotranspiration rates.

Advantages

Improving the water-use efficiency of a crop saves water at a most effective point, i.e., at the end of the water supply and delivery system. A 20 percent savings here may be equivalent to a manyfold increase in the supply at the watershed. Large areas of water-deficient and marginal lands could be made productive with appropriate plants, if coupled with management methods adapted for the area. Drought-resistant plants with high water-use efficiency could play a preeminent role in the progress of runoff agriculture (chapter 2).

Limitations

Genetic improvements take much time; however, selection of species, varieties, and ecotypes for most efficient water use may be important enough to justify active investigation. Cultivars and ecotypes must be selected not only for their water-use efficiency but also for their hardiness and drought resistance.

Stage of Development

Geneticists breeding plant varieties adapted to arid regions have been indirectly selecting plants that use water efficiently. But little or no research has been specifically directed to improving water use or determining the fundamental parameters in plant physiology that promote it. In relation to the opportunity, the effort now expended is small.

Needed Research and Development

There is a desperate need for selection of crop varieties (particularly for high-protein range and forage crops) that use less water. Fundamental to this is the need for simple, rapid tests and measures for water-use efficiency in plants.

Little specific breeding for drought resistance has been carried on; thus breeding programs are needed to select usable xerophytic (drought-resistant) plants. In general, physical characteristics such as water requirements and transpiration rates and anatomical and morphological characteristics do not provide simple and practical indicators of drought resistance. There is an urgent need for fundamental research in this area.

Basic research into photosynthetic efficiency and plant hormones is needed to determine if there is a biochemical method to rapidly identify and quantify water-conserving and xerophytic characteristics.

Even today, there is little recognition of the need for plant varieties with lower water requirements. A survey of promising crops and a collection of germplasm of varieties would make a valuable contribution to the development of arid-land agriculture.

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Contacts

Blackland Conservation Research Center, U.S. Department of Agriculture, Soil and Water Conservation Research Division, Temple, Texas 76501, USA (J. Ritchey)

Department of Agronomy, Cornell University, Ithaca, New York 14850, USA (E. R. Lemon)

Department of Agronomy and Plant Genetics, University of Arizona, Tucson, Arizona 85721, USA (M. A. Massengale, A. K. Dobrenz)

Department of Botany, Hebrew University of Jerusalem, Jerusalem, Israel (M. Evenari)

Department of Water Science and Engineering, University of California at Davis, Davis, California 95616, USA (R. M. Hagan)

Evapotranspiration Laboratory, Kansas State University, Manhattan, Kansas 66502, USA (E. T. Kanemasu)

Georgia Agricultural Experiment Station, Agricultural Research Service, U.S. Department of Agriculture, Tifton, Georgia 31794, USA (G. W. Burton)

International Crops Research Institute for the Semi-arid Tropics, 1-11-256 Begumpet, Hyderabad 16, A.P., India (R. Cummings, Director)

Negev Institute for Arid Zone Research, Beer Sheva, Israel (M. Forti)

U.S. Salinity Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Riverside, California 92502, USA (J. van Schilfgaarde)

U.S. Water Conservation Laboratory, Agricultural Research Service, U.S. Department of Agriculture, Phoenix, Arizona 85040, USA (W. L. Erhler)

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15 Controlled-Environment Agriculture

By encapsulating crops within specially developed enclosures, high agricultural productivity can be achieved with limited amounts of water. Water normally lost by seepage, evaporation, and transpiration (chapters 7, 8, 9, 13) is retained and reused within the enclosure. Thus, in net terms very little water is needed to produce the crop. Within the enclosure light, heat, water, humidity, carbon dioxide, nutrients, and pests are manipulated and balanced to produce yields often ten times larger than those of conventional outdoor agriculture. With special techniques most of the water can be low-quality water, such as seawater, otherwise unsuited to agriculture. In essence, this method places crops in an environment that can be so controlled that the upper limits of their yield potential are approached.

Methods

Enclosures may be transparent fiberglass structures, air-inflated bubbles, or low tunnels over the row of growing plants (FIGURES 73–75).

Closed-Environment Agriculture

One system pioneered by the University of Arizona's Environmental Research Laboratory and the University of Sonora, Mexico, can be used as an example of closed-environment agriculture. Plants are grown in inflated plastic greenhouses in which there is little or no connection with the outside atmosphere. Inside, the air is continuously cycled through a stream of water which humidifies and cools it. Brackish, silty, or sea water can be used; the humidification process leaves contaminants behind. Seawater is used at a test facility in Puerto Peñasco, Mexico (FIGURE 74). The plants are irrigated with high-quality water, but only a small amount is needed because

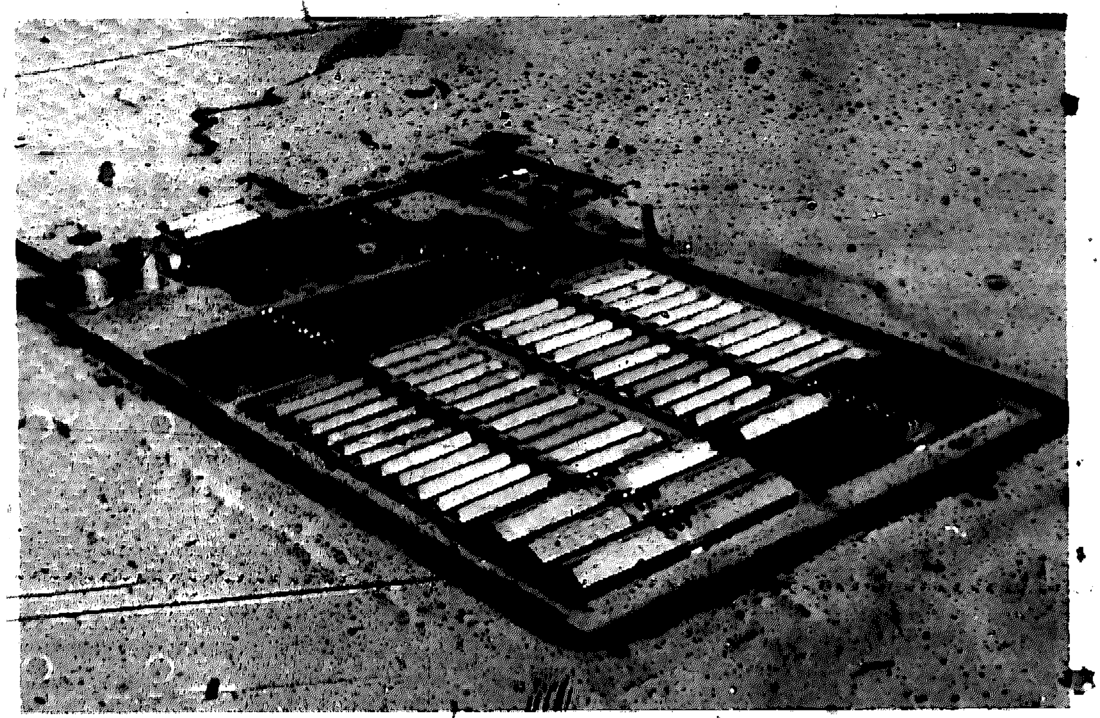

FIGURE 73 Controlled-environment complex in Abu Dhabi. Even in such inhospitable terrain very large quantities of agricultural produce can be produced (FIGURE 76). (Arid Lands Research Center, Abu Dhabi)

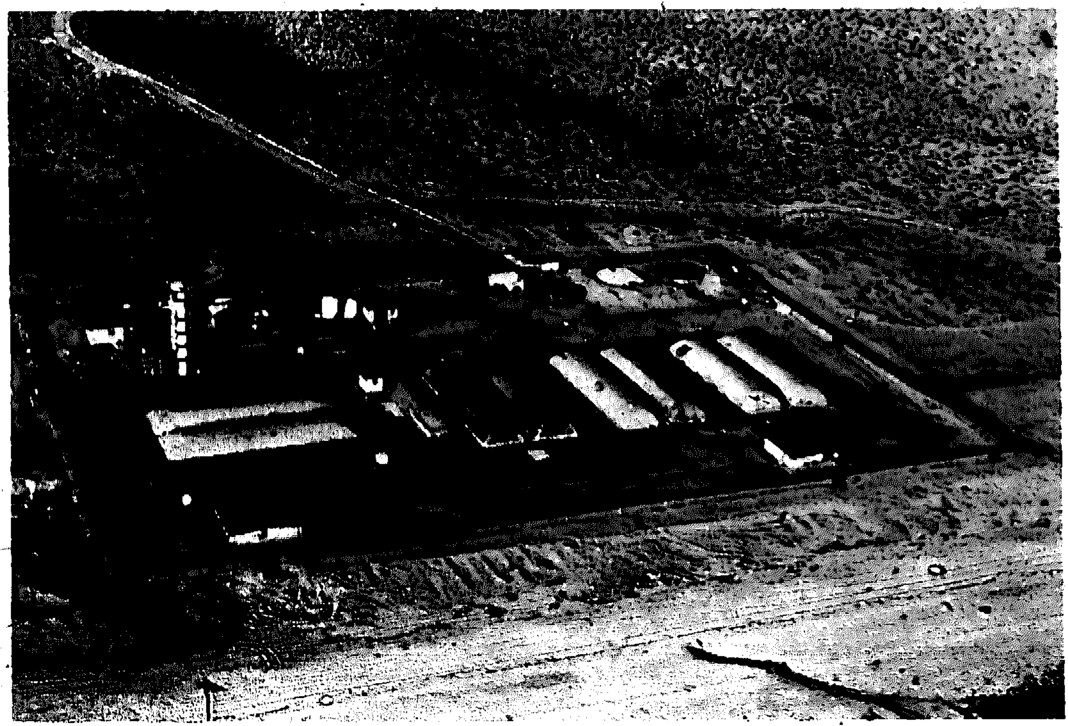

FIGURE 74 Controlled-environment complex in Puerto Peñasco, Mexico. (University of Sonora)

the high humidity suppresses transpiration and evaporation. Humidity is so high that in winter moisture condenses on the cool walls of the greenhouse and is collected and reused.

For photosynthesis to occur, carbon dioxide (CO_2) must be added because in the closed environment the plants quickly use up the available CO_2. In Puerto Peñasco scrubbed diesel-generator-exhaust gas, containing large amounts of CO_2, is introduced into the enclosure. Research to date shows that this apparently simple technique has promise, but problems remain, especially in removing minor contaminants that reduce crop production. In other closed-environment facilities, bottled CO_2 and CO_2 generators burning natural gas (which gives a cleaner exhaust than diesel fuel) are used to avoid the contamination.

FIGURE 75 Tunnel-enclosure for strawberries grown in Israel. (Ministry of Agriculture, Production and Extension Services, Israel)

Partially-Open-Environment Agriculture

In partially-open-environment agriculture fresh air is continuously supplied to the interior of the enclosure and returned to the outside atmosphere. The air is passed through a stream of water which can be of low quality. High-quality water is used for irrigating the crop, but because the high humidity suppresses evaporation and transpiration, the amount needed is still far less than that for standard agriculture. Since humidified air is continuously returned to the atmosphere, the total water requirement is more than that for closed-environment agriculture.

The University of Arizona has designed and provided consulting services for three commercial installations using the partially-open-environment technique. The first system installed (FIGURE 73) is in Abu Dhabi. In this facility the environment within the enclosures is humidified with seawater. Power is generated from a diesel electric engine, and waste heat from the engine powers a seawater-desalting plant. Desalted seawater irrigates 2 ha of controlled-environment agriculture. The expensive desalted seawater is used only to fulfill the relatively small requirement for irrigation water.

The second, and largest, commercial facility is in Tucson, Arizona, where 4 ha of partially-open-environment greenhouses use underground water for both environmental control (humidification) and irrigation. In Yuma, Arizona, a 2-ha complex is being erected to use brackish groundwater for environmental control and to desalt some of it for irrigation, using reverse-osmosis.

This system has considerable promise in arid areas where low-quality water is available and high-quality water is scarce.

Plastic Tunnels

One novel modification of controlled-environment agriculture uses low plastic tunnels placed over the plants (FIGURE 75) to reduce evaporation and transpiration losses. This system also allows environmental manipulation. According to one report,[46] carbon dioxide added to the tunnels caused cucumber plants to develop more quickly, to fruit earlier, and to yield up to 45 percent more than in standard agriculture. Lettuce gave a similar yield increase, and sweet peppers set more fruit and gave a 20 percent increase in yield. In Israel in 1966-67 over 1,200 ha were grown under such plastic covers. This method made it possible to produce vegetables very early in the season when supplies from conventional agriculture were meager and prices high.

[46] Kloner. 1967. (See Selected Readings.)

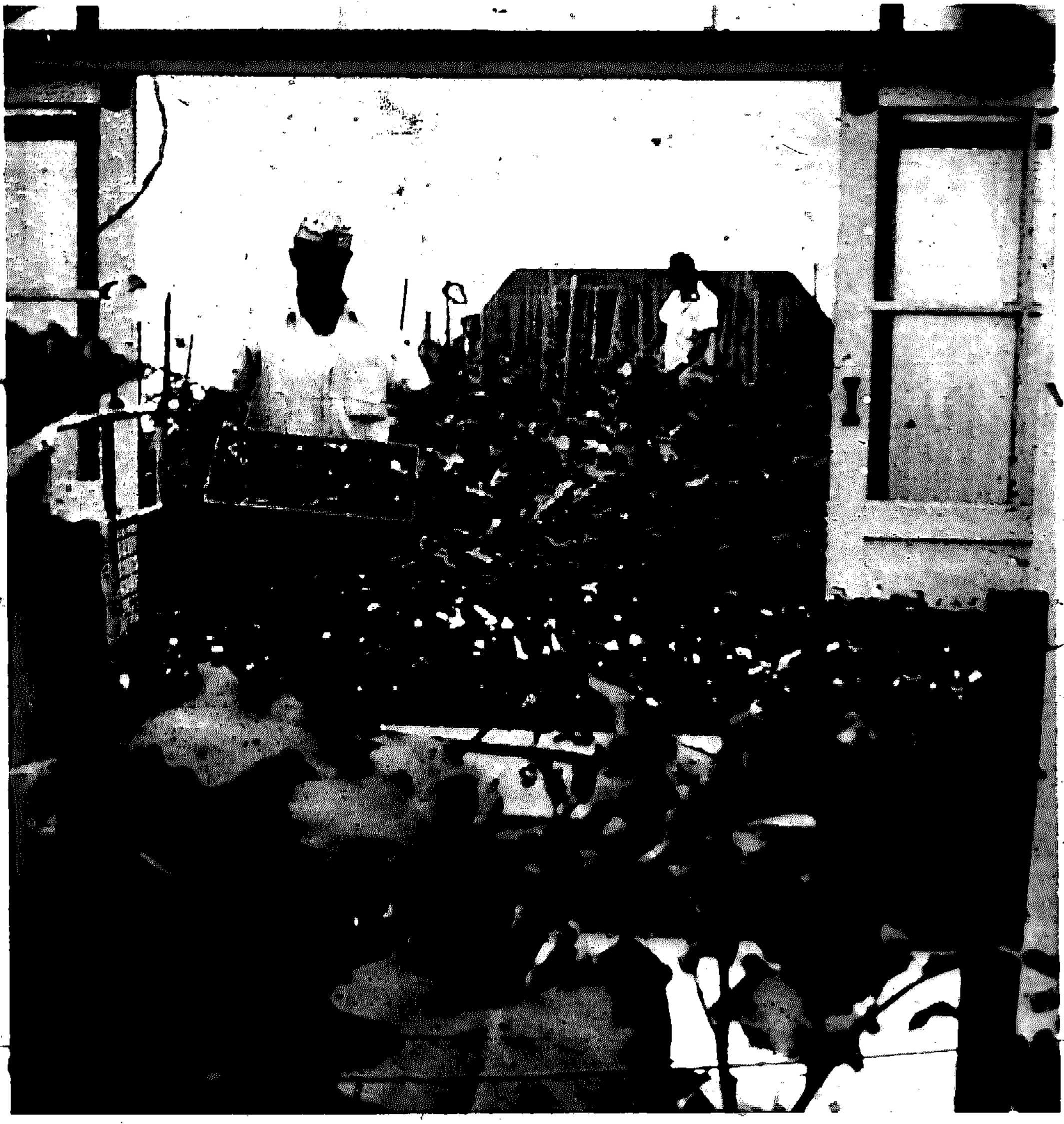

FIGURE 76 Quality tomatoes grow profusely in a controlled-environment greenhouse at Abu Dhabi. (Arid Lands Research Center, Abu Dhabi)

Advantages

Impressive productivity has been obtained in controlled-environment systems. Annual per-ha yields of 370 t of tomatoes and 600–750 t of cucumbers have been obtained, and it is possible to grow three to eight lettuce crops per year. Tomato, cucumber, and lettuce crops offer the most economic potential for this system today, but 16 other vegetables and flowers are commercially produced at the controlled-environment-agriculture facility in Abu Dhabi (FIGURE 76).

Although considerable quantities of water may be needed, the system offers very significant water savings in terms of the size of crop produced. If lower capital-costs could be achieved, whole villages, even in remote areas, could feed themselves with a single controlled-environment farm.

Limitations

The major limitation to closed-environment agriculture is the high initial capital investment. Based on University of Arizona experience, complete facilities, including culturing equipment, packing facilities, etc., cost approximately US$250.000–US$370,000 per ha, depending on the degree of sophistication. This means that only high-value crops can be grown at present. Water is still needed for cooling; hence installations will be limited to coastal areas or other locations where brackish or other water unsuitable for regular irrigation is available. Of course, the tunnel-enclosure system is much cheaper, but it, too, is expensive compared to costs of standard agriculture and only pays off when high-priced produce is grown.

Stage of Development

The closed-environment and partially-open-environment processes are now beginning to be commercialized. Because they are a very recent development, only a few facilities are now in operation, but more are under consideration. Plastic-tunnel agriculture is used to a limited extent in Israel.

Needed Research and Development

Lower cost systems would make controlled-environment agriculture increasingly attractive, and practical for use with lower priced crops. Particularly important in this regard is the need to develop low-cost CO_2 supplies.

It is also important to select varieties and develop crops that better tolerate high greenhouse temperatures and thus permit higher yields.

Other needs include:

- Roofing that selectively transmits the wavelengths of solar radiation that most promote plant growth;
- Use of hormonal or chemical sprays to protect plants against heat; and
- Studies of phytopathology and disease control in the hot and extremely humid environment within the enclosures.

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Contacts

Agricultural Research Organization, The Volcani Center, P.O.B. 6, Bet Dagan, Israel (H. Enoch and Y. Samish).

Department of Botany, Tel-Aviv University, 155 Herzl St., Tel-Aviv, Israel (Y. B. Samish)

Department of Vegetable Crops, Cornell University, Ithaca, New York 14850, USA (R. Shelldrake, Jr.)

Division of Agricultural Meteorology, Faculty of Agriculture, Hebrew University Rehovot, Israel (H. Enoch)

Dr.-Ing. Rolf Bettaque, 2057 Reinbek Bei Hamburg, Klosterbergenstr. 53, Germany

Environmental Research Laboratory, Tucson International Airport, Tucson, Arizona 85706, USA (C. N. Hodges)

Institut fur leichte Flachentragwerke, Universitat Stuttgart, 7000 Stuttgart 80, Germany (F. Otto)

Negev Institute for Arid Zone Research, Beer Sheva, Israel (E. Rappaport)

16 Other Promising Water-Conservation Techniques

Previous chapters have described water-conservation techniques that received special attention from the panel. Other developments, however, may prove to be equally valuable in the future. Some possibilities are briefly described.

Hydrophylic Soil Amendments

A considerable portion of irrigation water is ordinarily lost because of evaporation (chapter 8) or because it sinks below the root zone (chapter 12). Hydrophylic (water-attracting) chemicals can absorb water, holding it safe from evaporation or further dissipation. Soil mixed with such chemicals becomes spongelike, trapping and retaining water for an extended period. The water is available to plant roots which can draw on it as required. This method can be particularly important for increasing available water in sandy soils. Used as soil amendments, hydrophylic chemicals can enhance plant growth at low moisture levels. Plant roots and root hairs grow into and around the water-swollen hydrophylic material and extract water and nutrients from it.

Hydrophylic chemicals have been developed that can absorb up to 20 times their own weight of water. Although one such hydrophylic compound is being test-marketed in the United States, they are still basically experimental.

The water-holding capacity of sandy soils can also be improved by incorporating about 5 percent of crushed brown coal into the surface layer. This can double the available moisture, promote uniform soil temperatures, and mature crops earlier.[47] (See FIGURE 77.)

The very recent development of hydrophilic starch copolymers ("super slurpers") that absorb water up to 1,500 times their own weight has been reported.[48] Their role in arid-land agriculture remains to be tested.

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[47] Information supplied by Professor A. K. Turner, Department of Civil Engineering, University of Melbourne, Parkville, Victoria 3052, Australia.

[48] Reported by Dr. William M. Doane, Northern Regional Research Laboratory; U.S. Department of Agriculture, A.R.S., Peoria, Illinois 61604, USA.

FIGURE 77 Lettuce growing in porous sandy soil ammended with crushed brown coal, which has a large moisture-holding capacity. During experiments, the coal-treated plots remained moist on the surface while the untreated ones dried out. Yield from treated plots increased dramatically. (A. K. Turner)

Artificial Recharge of Underground Reservoirs

Water removed from underground aquifers can usually be replaced by natural recharge, but extensive well systems may withdraw enough water to exceed the replacement. In these cases, surface water can be used to replenish the water table, a process known as artificial recharge. In some places wells or pits are drilled to gain entry into the aquifer; elsewhere water is spread on the land, and, unaided, it percolates through the soil to the aquifer. This last method is appropriate for aquifers exposed at the surface, pits where they occur at shallow depths, and wells where aquifers are deep. These methods are quite inexpensive, require a minimum technical expertise for operation and management, and in areas with appropriate geohydrology are effective.

There is a growing interest in artificial recharging of groundwater because it provides readymade storage reservoirs, free from evaporation and protected against pollution, and because replenishing groundwater sources keeps neighboring saline waters from intruding into the aquifer and soil from subsiding into any empty space in a depleted aquifer. It can also be used to reclaim wastewater (chapter 4).

Rainwater harvesting (chapter 1) can also be used for recharging groundwater. This is being done experimentally at Wadi Shikmo in Israel. Water collected from a large watershed is permitted to percolate into an aquifer to provide increased water for otherwise overextended wells.

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خلاصه

يتناول هذا التقرير موضوع الوسائل الفنيه المتعلقه باستعمال المياه النادره في المناطق القاحله والمحافظة عليها ، ومثل هذه الوسائل لا تزال مجهولة بالنسبة للكثيرين رغم أنها تبشر بالخير والتقرير ليس دليلا فنيا متكاملا اذ أنه يكتفي بتوجيه اهتمام المسئولين عن الزراعه والتنميه الاجتماعيه والباحثين الى فرص الاستفاده من النظريات العلميه الثابته التي سيترتب على استخدامها في الغالب كثير من الفائده للمجتمع .

والوسائل الفنيه التي يناقشها التقرير يجب أن ينظر اليها على أنها وسائل مكمله للطرق التقليديه المستخدمه حاليا على نطاق واسع لتوفير المياه والتصرف فيها لا على أنها وسائل بديله لتلك الطرق . ومع هذا فان هذه الوسائل ستكون ذات نفع مباشر وان كان ذلك على المستوى المحلي وعلى نطاق ضيق ، في مجالات تنميه موارد المياه واستغلالها وخاصة في الاماكن البعيده ذات الموارد غير المنتظمه . وهذه الوسائل مع المزيد من البحث وعمليات الاقلمه ، قد تستطيع أن تصبح من حيث التكلفه منافسه للطرق التقليديه المستخدمه لزيادة المتوفر من المياه أو لتقليل الطلب عليها .

تتناول مقدمة التقرير باختصار عددا من النظريات التي لم تلق كثيرا من العنايه رغم مالها من اهميه في حسن استغلال المياه في المناطق القاحله أما الفصول التاليه فستتناول الوسائل

الفنيه بالتفصيل :

فتتعرض الفصول ١ ـ ٦ الى الوسائل الفنيه المستخدمه لزيادة موارد المياه ٠

وتتعرض الفصول ١ ـ ١٦ الى الوسائل الفنيه المستخدمه للمحافظة على المياه وتقليل الطلب عليها ٠ وفيما يلي ملخص لكل من هذه الفصول ٠

تجميع مياه الامطار

بامكان مياه الامطار المتجمعه من المنحدرات الطبيعيه ونقاط التجمع الصناعيه أن تكون موارد جديده لمياه ذات نوعيه جيده وبتكاليف منخفضه في الاراضي القاحله ٠

الزراعه باستخدام مياه المطر السائله

تشمل الزراعة من هذا النوع تجميع مياه المطر، ولكن المياه تستخدم مباشرة في الزراعة المهيئة خصيصا لهذا الغرض ٠

الري بمياه مالحه

تتوفر المياه المالحه بكميات كبيره ولكنها نادرا ماتستخدم لأنها تحد من نمو النبات ومن المحصول غير أن هناك براهين متزايده بأن المياه المالحه ، اذا استخدمت بعناية وفي ظل ظروف مواتيه ، يمكن أن تكون صالحة للري ٠

اعادة استعمال المياه

ان تزايد الطلب على المياه يجعل من الضرورى التوسع في اعادة استخدامها وان التطورات الفنيه في هذا المجال مثل اعادة تمرير المياه ومعالجتها قد تكون ذات أهمية كبرى في المستقبل ٠

الابار

عرف الانسان الابار المحفوره بالطرق اليدويه منذ آلاف السنين غير أن هذه الابار بدأ ينتشر استعمالها من جديد على أثر تطوير معدات والآت جديده لاقامتها وتعتبر القنوات والابار الافقيه وسائل للانتفاع من المخزونات المائيه الجوفيه دون حاجة الى استخدام المضخات ٠

موارد أخرى للمياه وطرق اكتشافها

يناقش هذا الفصل باختصار مواضيع التعدين من أجل الحصول على المياه الجوفيه تحلية المياه ، التقطير عن طريق استخدام الطاقة الشمسيه ، أستعمال الاقمار الصناعيه والطائرات لاكتشاف المياه في المناطق القاحله ، تجميع مياه الامطار ، امكانية الاستفادة من جبال الجليد كمورد من موارد المياه واستغلال الضباب والندىّ للحصول على مياه ٠

الاقلال من التبخر في السطحات المائيه

نظرا لكون التبخر عملية غير منظورة فانه لايعتبر مفيد للمياه

المخزونة رغم أن كميات كبيرة من الماء تفقد عن طريق التبخر سنويا وخاصة في المناطق القاحلة ، ولهذا فان وسائل الاقلال من التبخر تستحق اهتماما متزايدا كوسيلة من وسائل المحافظة على الماء .

وسائل فنيه جديده لمنع التسرب

يؤدى التسرب الى ضياع كميات كبيرة من المياه في الاقنية ومناطق تجميع المياه . وبامكان الوسائل والمعدات المعروفة حاليا أن تقلل من التسرب أو تمنعه كلية غير أن التكاليف لا تزال عاليه .

الاقلال من التبخر من سطح الارض

يؤدى تبخر الماء من سطح الارض الى ضياع المياه غير أن بالامكان الاقلال منه عن طريق استخدام أغطية أو حواجز من التبني . وفي كثير من الحالات تخدم هذه الاغطيه أهدافا أخرى كوقف زحف الرمال وتشجيع الزراعة باستخدام مياه المطر السائله .

الرى بالتنقيط

تعتمد هذه الطريقة التي طورت حديثا على اقامة شبكة من الانابيب المطاطيه توضع على التربة بين النباتات وتسيل المياه المحوله في هذه الانابيب على التربه المجاورة لكل نبات بمعدل معين سبق تحديده بدقة وفقا لاحتياجات النبات وبمقارنة هذه

الوسيله بوسائل الرى التقليدى يتبين أنه تم الحصول عن طريقها على محاصيل ممتازه بحد أدنى من المياه •

طرق الرى الحديثه الاخرى

يناقش هذا الفصل بالصور بعض وسائل الرى البسيطه التي لاتتعرض اليها الكتب الدراسيه والفنيه في العاده رغم فائدتها للرى في المناطق القاحله •

الاقلال من ضياع المياه عن طريق التسرب

كثير من المناطق الواسعه القاحله ذات التربه الرمليه لاتستخدم في الزراعه لان المياه تترسب الى ماتحت منطقة الجذور بسرعة فائقه مع عدم وجود مياه اضافيه تعوض هذا النقص • وهناك الان وسائل يجرى تطويرها لاقامة حواجز صناعيه تحت التربة تمنع المياه والمواد الضرورية لغذاء النبات من الترسب السريع أو تحد منه •

اختيار المحاصيل وادارتها بطريقة تضمن حسن استعمال المياه

•لم تتم حتى الان بحوث كافيه لتطوير أنظمة للرى في المناطق القاحله تضمن حسن استغلال المياه • ولاتزال هناك امكانيات كثيرة بامكان البحث العلمي أن يتطرق اليها سواء كانت في مجال خصائص النبات الموروثه أو في مجال الهندسه •

الاقلال من التبخر في أوراق النبات

ان حوالي ٩٠٪ من المياه التي تمتصها جذور النباتات تتبخر من الاوراق في الجو . واذا ماوجدت وسائل عمليه للاقلال من هذا التبخر فمن المحتمل أن تتم وفورات كبيره في كمية المياه اللازمة لانتاج محصول معين .

الزراعة في بيئة تم التحكم فيها

بالامكان عن طريق زراعة النبات في محتويات شفافة تمنع تسرب المياه الاقلال من كمية المياه الضائعه الى درجة كبيرة وبالامكان التحكم في الجو المحيط بالنباتات بطريقة تضمن مضاعفة الانتاج . ان مثل هذه الوسائل باهظة التكاليف ولكن يمكن عن طريقها الوصول الى انتاجية زراعية عاليه بكميات قليلة من المياه .

بقية الوسائل الاخرى المشجعة للمحافظة على المياه

يناقش هذا الفصل باختصار وسائل التحكم في التربة بطريقة تضمن المحافظة على المياه وطريقة اعادة تغذية المخزونات الجوفيه صناعيا .

Français

Introduction et Résumé

Le présent rapport traite de techniques peu connues mais prometteuses pour l'utilisation et al conservation des ressources aquatiques insuffisantes dans les zones arides. Ce document n'est pas un manuel technique; il vise à appeler l'attention des responsables et chercheurs de l'agriculture et du développement communautaire sur certaines possibilités d'exploiter des idées valables et d'une portée sociale probablement élevée.

Il faut, pour le moment, considérer les techniques exposées comme des adjuvants, et non comme des variantes, aux méthodes normales de fourniture et d'exploitation de l'eau à grande échelle. Elles doivent présenter un intérêt local immédiat pour le développement et la conservation des ressources aquatiques à petite échelle, surtout dans les régions écartées ne disposant que d'un approvisionnement intermittent. Avec des recherches et une adaptation plus poussées, certaines de ces techniques peuvent s'avérer d'un mérite économique concurrentiel à l'égard des méthodes habituellement employées pour augmenter l'alimentation en eau ou pour réduire la demande.

L'introduction de ce rapport présente brièvement un certain nombre d'idées souvent négligées, qui ont leur importance pour l'exploitation de l'eau dans les terres arides. Les chapitres qui la suivent traitent de techniques particulières: les chapitres 1 à 6, de celles qui permettent d'augmenter les eaux disponibles; les chapitres 7 à 16, de celles grâce auxquelles on peut conserver l'eau et réduire la demande. On trouvera ensuite un résumé de chaque chapitre.

Collecte de l'eau de pluie

L'eau de pluie recueillie au pied des versants de collines et dans des bassins artificiels peut fournir des ressources d'eau supplémentaires à bas prix et de haute qualité pour les terres arides.

Agriculture par ruissellement

Elle implique la collecte de l'eau de pluie, mais l'eau est utilisée directement dans des systèmes agricoles spécialement conçus à cet effet.

Irrigation par eau salée

L'eau salée est facilement disponible, mais on l'utilise rarement parce qu'elle réduit la croissance et le rendement des plantes. Il est de plus en plus prouvé qu'avec des précautions, et dans certaines conditions favorables, on peut avantageusement irriguer avec l'eau salée.

Remploi des eaux

L'augmentation de la demande en eau impose que l'on réutilise beaucoup plus l'eau. Il est possible qu'à l'avenir l'évolution technique (recyclage et traitement perfectionné des eaux) revête une grande importance.

Puits

Le puits creusé de main d'homme, méthode qui remonte à des milliers d'années, connaît un regain de popularité avec l'aide de nouveaux matériaux et appareils de construction. Les "Qanats" et les puits horizontaux sont des procédés qui permettent de capter les eaux souterraines sans employer de pompes.

Autres sources d'eau et méthodes de détection

Dans ce chapitre, on évoque rapidement le captage des eaux phréatiques, la désalinisation, la distillation solaire, l'utilisation des satellites et des avions pour le repérage de l'eau dans les terres arides, l'augmentation de la pluviosité, la possibilité de se servir des icebergs comme source d'eau; enfin, la collecte de la rosée et du brouillard.

Réduction de l'évaporation des surfaces aquatiques

Comme l'évaporation est invisible, on la considère rarement comme une sérieuse cause d'épuisement des eaux accumulées, mais les pertes annuelles dues à l'évaporation, surtout dans les zones arides, sont considérables. L'abaissement de l'évaporation mérite qu'on lui prête de plus en plus d'attention comme moyen de conserver l'eau.

Nouvelles techniques de lutte contre les infiltrations

L'infiltration est à l'origine de graves déperditions d'eau dans les canaux et retenues. Les matériaux et techniques modernes peuvent réduire ou supprimer l'infiltration, mais les frais demeurent élevés.

Ralentissement de l'évaporation des surfaces pédologiques

Cette évaporation provoque une déperdition d'eau mais on peut la diminuer par des "couvertures" ou déchets organiques. Dans bien des cas, ceux-ci remplissent également d'autres rôles: arrêter la progression du désert ou favoriser l'agriculture par ruissellement.

Irrigation par filets d'eau

Cette méthode récemment mise au point utilise un système de tuyaux en matière plastique placés sur le sol parmi les plantes. L'eau circulant dans les canalisations s'écoule sur le sol à côté de chaque plante à un rythme soigneusement adapté aux besoins de la plante. Par rapport à l'irrigation traditionelle, on a obtenu des rendements agricoles excellents avec un volume d'eau minimal.

Autres nouvelles méthodes d'irrigation

On présente, au moyen d'illustrations, quelques méthodes d'irrigation simples, laissées de côté dans les ouvrages techniques ou les manuels, et susceptibles de rendre des services dans les terres arides.

Allègement des pertes d'infiltration

Il y a, dans les zones arides, de vastes étendues de terrain sablonneux qui ne servent pas à l'agriculture parce que l'eau s'enfonce trop rapidement au-dessous du niveau des racines et que l'on ne dispose pas du supplément d'eau d'irrigation qui permettrait de compenser cette perte. On met actuellement au point des techniques visant à créer des barrières artificielles d'humidité souterraine destinées à empêcher ou à réduire le filtrage de l'eau et des éléments nutritifs.

Choix et exploitation des cultures en vue d'une utilisation plus rationnelle de l'eau

On n'a pas réalisé grand chose en fait de procédés de culture permettant d'utiliser efficacement l'eau dans les terres arides. Beaucoup de possibilités de recherche restent à explorer, de la génétique phytologique à la technologie.

Réduction de la transpiration

Environ 99 pour 100 de l'eau absorbée par les racines des plantes est libéré dans l'air par les surfaces des feuilles. Si l'on peut trouver des moyens pratiques de réduire ce phénomène, on parviendra à réaliser d'énormes économies dans le volume d'eau nécessaire à la culture d'une plante donnée.

Agriculture en milieu surveillé

En cultivant les plantes dans des compartiments étanches mais transparents, on peut beaucoup diminuer la quantité d'eau normalement perdue, et on peut aussi régler l'atmosphère, autour des plantes, de manière à porter la productivité au maximum. Ce sont là des méthodes coûteuses, mais qui permettent d'atteindre un rendement agricole élevé avec de petites quantités d'eau.

Autres techniques prometteuses de conservation de l'eau

Ce chapitre aborde brièvement les améliorations pédologiques qui favorisent la conservation de l'eau, et la reconstitution artificielle des réserves phréatiques.

Español

Introducción y resumen

Este informe se refiere a tecnologías poco conocidas pero que ofrecen buenas posibilidades para el uso y conservación de los escasos recursos de agua en regiones áridas. No es un manual técnico, su propósito es llamar la atención de funcionarios e investigadores interesados en el desarrollo agrícola y comunal sobre oportunidades de seguir conceptos bien fundados que pueden tener un probable alto valor social.

Las teorías expuestas deben considerarse, por ahora, mas bien como complementos que substitutos de métodos normales de suministro y administración de aguas. Deberán constituir un valor local inmediato en cuanto al desarrollo y conservación de aguas en pequeña escala, especialmente en regiones remotas donde la provisión de agua es intermitente. Con más investigación y adaptación, algunas tecnologías pueden demostrar que pueden competir económicamente con los métodos normales para aumenter el suministro de aguas o reducir la demanda.

En este informe se presentan brevemente varios conceptos, a menudo no tenidos en cuenta, pero que son importantes para la administración de aguas en tierras áridas. En los capítulos siguientes se exponen técnologías específicas. Los capítulos 1 al 6 se refieren a tecnologías para mejorar el suministro de aguas y los capítulos 7 al 16 a tecnologías para reducir la demanda. A continuación se hace un informe de cada capítulo.

Recolección de agua de lluvia

El agua de lluvia recogida de las laderas de los montes y los colectores hechos a mano pueden representar nuevas fuentes de agua de bajo costo y buena calidad para tierras áridas.

Agricultura de derramamiento

La agricultura de derramamiento requiere la recolección de agua de lluvia pero el agua se usa directamente en sistemas agrícolas diseñados específicamente al efecto.

Regadío con agua salina

El agua saladá es fácil de obtener ampliamente pero se utiliza raramente debido a que restringe el crecimiento y la producción de las plantas. Actualmente se está acumulando evidencia que con cuidado y bajo ciertas condiciones favorables se puede utilizar agua salada beneficiosamente para regadío.

Reutilización de aguas

La creciente demanda de sumnistro de aguas impone la necesidad de aumentar al máximo la reutilización de las aguas. Los desarrollos técnicos, tales como el reciclaje y el tratamiento de aguas de albañal pueden tener gran importancia en el futuro.

Pozos

Los pozos excavados a mano, una technología que comenzó miles de años atrás, está volviendo a ganar popularidad con la ayuda de nuevos materiales y equipo de construcción. Los pozos "Qanats" y horizontales son métodos de derivación de aguas subterraneas sin utilizar bombas.

Otras fuentes de aguas y métodos de detección de agua

En este capítulo se hace una breve mención a la "minería" de aguas subterraneas, desalinización, destilación, utilización de satélites y aeronaves para detectar fuentes de aguas en tierras áridas, incremento de lluvias, la posibilidad de utilizar témpanos de hielo como fuentes de agua y la recolección de rocío y niebla.

Reducción de la evaporación de las aguas de superficie

Debido a que la evaporación es invisible, con frecuencia no se considera un problema grave de merma en las aguas almacenadas, pero las pérdidas anuales debidas a la evaporación, especialmente en tierras áridas son enormes. La reducción de la evaporación merece un mayor interés como un medio para la conservación de los recursos de aguas.

Nuevas técnicas para el control de la permeabilidad

La permeabilidad causa graves pérdidas de agua en canales y embalses. Utilizando materiales y técnicas modernos se puede reducir o eliminar la permeabilidad, pero el costo aún sigue siendo muy alto.

Reducción de la evaporación de la superficie del suelo

La evaporación de la superficie del suelo representa una pérdida de agua, pero se puede reducir cubriendo el suelo con cubiertas o capas protectoras. En muchos casos las cubiertas sirven de funciones complementarias tales como impedir la invasión del desierto o la promoción de la agircultura de derramamiento.

Regadío por goteo

Este método de regadío recién desarrollado usa un sistema de tuberías de plástico colocadas en el suelo entre las plantas. El agua que pasa a través de las tuberías gotea dentro del suelo al lado de cada planta a un régimen cuidadosamente calculado en función de las necesidades de las plantas. Comparado con el regadío convencional, con este método se han obtenido excelentes rendimientos de cosechas con una mínima cantidad de agua.

Otros novedosos métodos de regadío

Se presentan gráficamente otros métodos de regadío simples, no tenidos en cuenta en manuales ni en libros técnicos, que tienen un beneficio potencial para las teirras áridas.

Reducción de pérdidas por percolación

Vastas extensiones de suelo arenoso en tierras áridas no se utilizan para la agricultura debido a que el agua se escurre por debajo de la raíz de la planta demasiado rápido y no se dispone del agua necesaria para compensar esta falta de regadío. Actualmente se están desarrollando técnicas para producir una barrera subterránea artificial para impedir o restringir que el agua y los nutrientes se pierdan.

Selección y administración de cosechas para utilizar el agua más eficientemente

Es muy poco lo que se ha hecho para diseñar sistemas eficientes de aguas para la agricultura en tierras áridas. Todavía quedan por explorar numerosas oportunidades desde la genética de plantas hasta la ingeniería agrícola.

Reducción de la transpiración

Cerca de un 99% del agua absorbida por las raíces de la planta es devuelta al aire por las superficies de las hojas. Si se pueden lograr medios prácticos para reducir este proceso, se podrán obtener considerables ahorros de agua necesaria para producir una cosecha determinada.

Agricultura de medio ambiente controlado

Mediante la siembra dentro de recintos de protección, estancos al agua, se puede reducir considerablemente la cantidad de agua que se perdería normalmente y la atmósfera alrededor de las plantas se puede manejar para aumentar al máximo su productividad. Estos son sistemas costosos pero con ellos se puede lograr una productividad agrícola alta con pequeñas cantidades de agua.

Otras técnicas de conservación de aguas prometedoras

En este capítulo se hace una breve mención a reformas en el suelo para conservación de aguas y recarga artificial de depósitos de agua subterráneos.

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