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Scientific Advances Most Needed for Progress in Irrigation

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Scientific advances most needed for progress in irrigation

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In the last half-century the application of scientific advances in irrigation has been largely confined to the developed countries. In the vast irrigated areas of Asia, progress in the adoption of new technology has been disappointing except for the introduction of new crop varieties. The massive expansion in the total irrigated area of Asia has been largely based on traditional technology. The world is waking up to this technological gap and beginning to analyse its causes. The current gap is illustrated by the fact that irrigated cereal yields in Asia are less than half those of the U.S.A. or Australia. In Africa, the gap is even wider.

It is argued that many recent technologies, including those of micro-irrigation, systems analysis and automatic control structures, are not applicable to Asia and Africa. We have to research new ways of applying them and we need to expand the science of irrigation in more appropriate forms.

Among the needs for scientific advance considered in the paper are improved water management, use of saline groundwater, lower cost methods of subsoil drainage and improved management technology involving wider and better use of communications and management information systems.

The paper examines these and other issues and suggests high-priority topics and strategies for research and development.

1. Introduction

The rapid expansion of irrigation in the world in recent time has taken the total irrigated area from about 94 Mha in 1950 to an estimated 271 Mha in 1985, of which 75% is in developing countries. As may be seen from table 1 this expansion has taken place at about the same rate in most continents, but in absolute terms the increase in irrigated area in Asia is most dramatic. It has averaged 3.4 Mha per year over that period.

Unfortunately technological progress has not kept pace with irrigation expansion with the result that there are vast areas of land in need of modernization, including systems that have been developed in recent years. In many developing countries there is an additional problem that because of a lack of good management and proper maintenance many systems require both rehabilitation and modernization.

In this same period, after the Second World War, there have been important technological advances in irrigation and drainage in the developed countries. These advances have been stimulated by economic forces, including the relatively large increases in the costs of labour and energy, and also by agronomic factors such as the introduction of new crop varieties that give better response to farm inputs and particularly to water. The question therefore arises why the advances in technology in the developed countries have not had greater impact in the developing countries. Put in another way, why have the developing countries continued to build new irrigation schemes that are much the same in concept and design as those developed at the turn of the century?

TABLE 1. GROSS IRRIGATED AREAS (MILLIONS OF HECTARES) BY CONTINENT

	1950	1960	1970	present estimate
Europe (incl. part U.S.S.R)	8	12	20	29
Asia (incl. part U.S.S.R.)	66	100	132	184
Africa	4	5	9	13
North America	12	17	29	34
South America	3	5	6	9
Australia and Pacific	1	1	2	2
totals	94	140	198	271

The answer may in part be that in countries where inadequate attention is given to operation and maintenance, it is unlikely that much priority will be given to technological advances. To some degree, lack of technological progress and neglect of operation and maintenance represent attitudes that might be linked.

Another more objective explanation is that the technological advances of recent years are often not appropriate to the developing countries, in that they are either unsuited to the local conditions or they are not economically viable where yields and hence gross production values per hectare are low.

To give specific examples, the major advances that have taken place in sprinkler and drip irrigation have found little or no place in the developing countries, except for specialized crop production on well managed estates. Although these methods have the inherent advantages of high irrigation efficiency, they also have a high capital cost that cannot be justified in situations where the water delivery from source is unreliable or where the full complement of other farm inputs is either not available or not applied in sufficient quantity to achieve the necessary levels of production.

There is a need to apply research and development more specifically to the needs of developing countries in irrigation and drainage. Such an approach has already been successful in agricultural research, and it now remains to extend the concepts of the work sponsored by C.G.I.A.R. (Consultative Group for International Agricultural Research) in the irrigation and drainage engineering sector.

The general objective of this paper is to identify some of the more important constraints in irrigated crop production and in drainage and to suggest priority items for research and development programmes. Measures to remove or alleviate constraints that will offer good prospects of early returns and have a widespread effect in developing countries are identified. Emphasis is placed on improvement in management technology – both *water* management and *project* management (which has the more specific objective of the economic optimization of production). Other topics deemed to have immediate priority are the use of low-quality waters and the need for lower cost drainage works. A reference is also made to bilharzia control, because the disease remains so widespread in irrigated areas despite the excellent advances made in recent years.

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2. Project management technology

Impact of management standards on production

The biggest single constraint in raising production levels from the existing irrigated land is weakness in project management. It is now generally recognized that major national and international efforts have to be addressed to this problem if irrigation is to make an appropriate contribution to the growth in agricultural production.

The impact of any potential improvements in productivity from irrigated land can be judged from table 2, which shows the estimated contribution of irrigated cropping to the total food supply in selected countries.

Table 2. Estimated contribution of irrigation to food supply in selected countries

country	irrigated food production (percentage of total food supply)
India	55
Pakistan	80
China	70
Indonesia	50
Chile	55
Peru	55

The reason why management standards have stagnated and at times declined is often attributed to the long-established bureaucratic nature of irrigation agencies, with an inadequate integration of all those disciplines that make essential contributions to the economics of irrigated crop production. These are not only engineering and agriculture but also those of bankers, economists, accountants, and sociologists.

A new factor that influences progress in irrigation management is the modern social desire for user participation in a corporate activity. This is recognized by the emphasis now given to farmer participation through cooperatives and other forms of association in countries such as Morocco (Ait Tihyaty *et al.* 1984) and the Philippines (Bagadion 1984).

The new approach to management issues

Some 20 years ago there was a tendency to think that irrigation management deficiencies might be corrected simply by a more rigid application of conventional rules and by institutional changes. The results have often been poor and sometimes negative and it is clear that these measures alone are not sufficient. Today the approach is more progressive. It begins with research into 'cause and effect', which is followed by trial, and only then comes adoption of the selected management structure on a full scale.

Some pioneer research work has been done by the Overseas Development Institute of London. In 1984 the International Irrigation Management Institute (I.I.M.I.) was established in Sri Lanka, financed by a support group of members drawn from C.G.I.A.R. A unit of I.I.M.I. is shortly to be set up in Pakistan and more should follow in other countries. The objective of I.I.M.I. is to find ways of improving the performance of irrigation systems through management innovations. Although management of water will receive primary focus, other factors will be the subject of research including farm inputs, finance, marketing, and sociological factors.

Research in project management

Research institutes in irrigation management practices need to approach their work in two main stages. First, there is a need to identify the constraints that at present control the indices of production, and to determine how they can be lifted or alleviated *without* modernization of the physical works and equipment. Secondly, there is a need to formulate the desired forms of modernization required to maximize economic production. The first stage will involve the study of a number of conventional management issues, the institutional structures, and the degree to which they respond to current social, economic, and market forces.

The second stage of irrigation management research should be to evaluate the shortcomings of the existing physical components of irrigation systems and the extent to which these shortcomings hinder the application of sound management technology and hence productivity. A further result of this stage should be to identify technical weaknesses which should be the subject of further scientific research. This is a more difficult and complex stage than the first. It involves not only the hydraulic works and drainage systems, but all the associated infrastructure including that of transportation, processing and communications.

In most situations, modernization will be both slow and costly to implement. Some 150 Mha of irrigated area in the world is in need of modernization in one form or another. The modernization process will thus have an indefinite time horizon given that the new developments of today will eventually find a place in the modernization cycle.

The components of a modernization programme vary from area to area, but the more fundamental objectives are better information systems and communications, improved water management, more effective supplies of farm inputs, improved roads and other infrastructure, and a more widely based management structure but with stronger farmer participation. The paragraphs that follow will focus on two of these topics, namely water management and information systems.

Water management

An interdisciplinary and bureaucratic process

Irrigation water management is not simply a matter of physical control of flows. In common with project management as a whole, it involves a wide array of social, climatic, economic, hydrological, hydraulic, environmental, and other factors that are less amenable to change than, for example, the remodelling of canals and the introduction of better control structures. Furthermore, in regions with a long tradition of irrigation the situation is constrained by land tenure, prescriptive water rights, by bureaucratic structures that have come about within the irrigation agencies that operate and maintain the systems and, in some situations, by international water issues.

The three stages of water management

Water management for irrigation may be divided into three stages. First, the resource management of the bulk supplies at the reservoirs or other point sources; second, the conveyance from the point sources to the farming units; and third, the management within the farming units.

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Resource management

Resource management has made technological progress in recent years aided by such tools as satellite imagery, computer models and improved techniques in flow prediction. However, the general progress is still disappointing in many developing countries. This is the result not only of technical and economic difficulties but also of administrative and political disputes, particularly where international or interstate waters are involved. Of the three stages in water management, that of resource management is, however, the least critical in its effects on crop production.

Conveyance-system management

It is in the second stage, namely the conveyance from point source to farming unit, where the standards of efficiency are unacceptably low.

Conveyance systems in developing countries are mostly designed to deliver water in accordance with *rigid* schedules that have little real flexibility. It is left to the cultivators in the farming unit to adjust their cropping calendars as best they can to make good use of water supplies in time and volume. In some situations the rigidity is partly dictated by hydraulic requirements to achieve a non-silting and non-scouring régime in the canal systems. Canals that draw from silt-laden sources are designed to operate in 'regime' according to the theories developed, for example by Kennedy and Lacey, to cite two well known British research workers in irrigation. The normal operating practice in the 'rigid-schedule' systems is to maintain the flow in the conveyance systems at or near fully supply level so long as the water resources are available. During times of shortage the flows in the distributary canals are reduced to about 85% of full capacity. Below that level of water availability, flows in the distributaries are rotated so as not to depart from a non-silting régime. Thus, although in principle the method of rigid scheduling is based on the concept of 'constant-flow–constant-frequency', there is in fact some variation of both flow and frequency. Furthermore, in times of low crop water demand, such as during periods of rainfall, reductions are made in the deliveries again with adjustment of both volume and frequency of flows.

The rigid system, with some variations, is applied broadly in many of the large irrigation systems of south Asia. It was well adapted to the conditions at the time of its introduction when cropping intensities were low (about 25% in summer and 50% in winter); when silt contents were high at the points of diversion, and when water was generally plentiful. Things have now changed, in that cropping intensities have more than doubled, storage dams have reduced the silt content of the water at the diversion points, and water supplies have been almost fully exploited in many regions. The higher cropping intensities and the shortage of water resources make it imperative to move towards a more flexible conveyance system with much lower losses (both seepage and escapage losses), which will also give more reliable and timely deliveries to the farmers. The crucial issue for the time being is the high level of losses. Without a reduction of losses there is little opportunity to provide more adequate and timely supplies to meet crop water requirements.

In a survey of irrigation systems in developed and developing countries Bos & Nugteren (1974) produced data which indicated that although conveyance efficiencies are higher in developed than in developing countries, it is not so much the type and intensity of control structures that is the cause of high losses but more a matter of the level of management applied. The figures quoted are given in table 3.

To give some measure to these differences in efficiency a 10% absolute improvement in a country such as Pakistan would permit *ca.* 2 Mha of additional crops to be irrigated annually.

It has been argued by some workers in irrigation management that little can be done to improve conveyance efficiencies in developing countries without the installation of a much better system of control structures on the canals. This is only true if one assumes that little or nothing can be done about the other constraints and a continuation of a low level of management capability is inevitable.

Table 3. Irrigation conveyance efficiencies (percentages) for different control structures

	temporary	fixed	movable gates	automatic	others	weighted average
selected developed countries (32 samples)	77	74	72	72	92	74
selected developing countries (28 samples)	50	65	69	—	48	65

It is clear from many activities that modern automation and use of computers permits good management with economy in human resources. This is an important consideration in those developing countries in which trained and experienced managers are scarce. The ultimate choice between automation in an irrigation conveyance system and management training will no doubt involve a compromise. The correct solutions for each situation will differ and call for much study and research.

Water management in farming units

At the level of the farming unit the problems of management are more complex than in the conveyance systems. There is, of course, a close relation between the efficiency achieved at farming-unit level and standards of management in the conveyance system. Where water is not delivered in the correct amounts and at the right times to the farming unit the efficiency of distribution is adversely affected.

At the farming-unit level the efficiencies may be divided between distribution efficiency and field application efficiency. It has been found that where flows are rotated between farmers the distribution efficiencies are much lower than for continuous flows. For rotational flows, distribution efficiencies as low as 50% have been recorded but a more general figure is *ca.* 75%. For continuous-flow systems, such as in rice areas, over 90% can be expected.

Field application efficiencies vary with method of irrigation, type of soil and standard of farm management. Bos & Nugteren (1974) have quoted the figures given in table 4.

Overall irrigation efficiencies

A typical Asian situation has 75% distribution efficiency and 60% application efficiency and thus the overall efficiency within the farming unit is about 45%. If, in addition, a conveyance efficiency of 65% is assumed, the overall efficiency is about 30%. By contrast, in a country such as the U.S.A. with a well-managed sprinkler system, the overall efficiency can

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TABLE 4. FIELD APPLICATION EFFICIENCIES (PERCENTAGES) AS FUNCTION OF METHOD OF IRRIGATION

	average	basin	furrow	border	sprinkler
developed countries	60	59	58	57	68
developing countries with mainly mixed crops	53	56	54	47	n.a.[a]
developing countries with mainly rice	32	32	n.a.	n.a.	n.a.

[a] Marked as n.a. for not applicable.

be as high as 60 %. With the surface-application method a well run system in the U.S.A. would have an overall efficiency of about 37 %, divided as follows: conveyance 75 %; distribution 85 %; farm application 58 %; overall 37 %.

The wide margins between traditional and advanced irrigated crop production

The figures on irrigation efficiency quoted above demonstrate the wide margins that exist between those achieved in the large irrigated areas of the developing world and those of the more advanced systems. Taken together with the gap that exists in irrigated crop yields, which is indeed partly linked to differences in water management standards, the potential increase in agriculture production in developing countries is enormous. A fundamental requirement is to find ways of improving water management that are suited to the social, economic, and physical conditions of each region and then to seek ways of implementing change so that the gap in yields can be at least partly closed.

Key topics for research in water management

Irrigation research, as with most other forms of agricultural research, including the plant-breeding programmes of the international centres, is location-specific, and water management research is no exception to this generalization. Some of the key topics that call for research in irrigation water management are as follows.

(*a*) *Design and operational process*

(i) How much does better flexibility in water scheduling raise efficiency and crop production when compared with the traditional rigid systems?

(ii) What are the feasible ways in which more flexibility can be achieved, such as canal remodelling, better scheduling procedures, and stronger user participation?

(*b*) *Institutional and social process*

(i) What are the correct relations and division of responsibilities between farmers and irrigation authority in water management?

(ii) What are the correct incentives to good water management at farm level?

(*c*) *Input and financial factors*

(i) Relations between water and other inputs.

(ii) Influence of cost recovery for irrigation on farming efficiency.

Management information systems

Good quality and prompt information services are fundamental requirements in irrigation project management, but many authorities have not moved far from the traditional use of telephones, forms, and messengers. Furthermore, the efficiency of these traditional media has declined and in some cases has become almost ineffective. Modern technology in communications, telemetry and automatic control systems offer immediate and low-cost opportunities to improve management information systems. Once introduced, such systems have the advantage that economies can be made in the number of trained managers required for a given project and such human resources are likely to remain scarce in developing countries for a long time.

To establish a centralized management information system, the minimum requirement is a central computer with a data conversion facility using conventionally transmitted data. Later, as the information system becomes more developed, there should be a gradual dispersal of data-entry processing to bring data conversion and validation closer to the sources of information.

Figure 1 shows in simplified form a typical management information flow and interface chart for the agricultural subsystem. Similar charts can be prepared for total information and for other subsystems, including engineering, finance and stores.

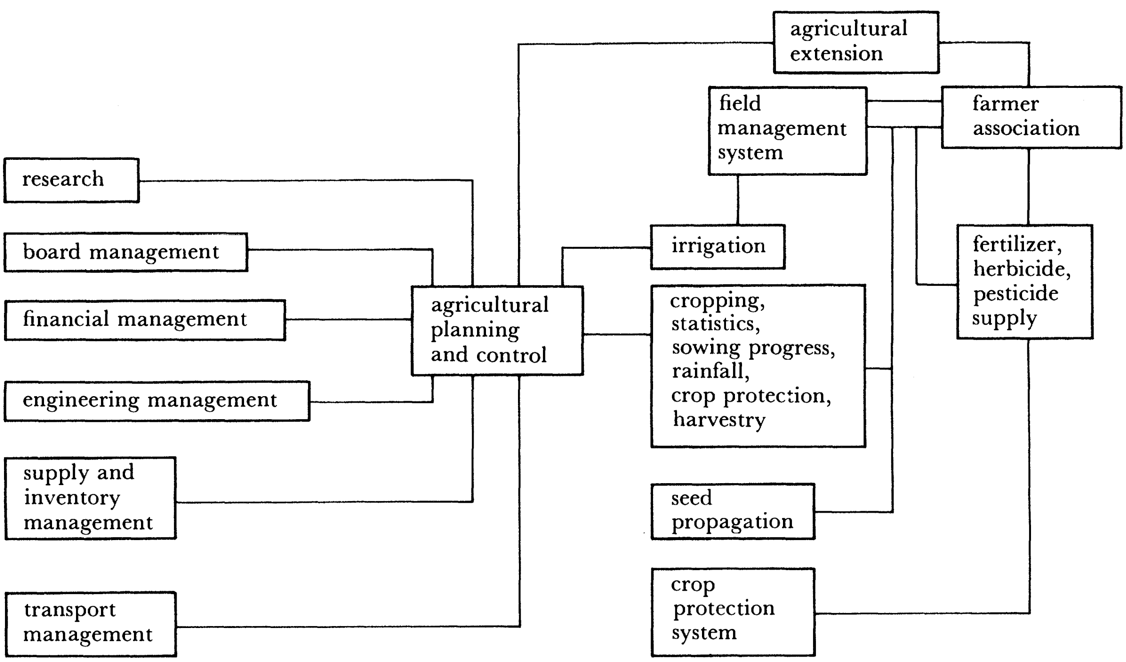

Figure 1. Simplified flow chart for project management.

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3. Use of low-quality waters

Saline waters

In almost all arid and semi-arid zones where irrigation is practised there are ever-growing problems of salinity. The basic cause is the steady build-up of salt in the groundwater which, coupled with a rising water table, brings about toxic conditions in the plant root zones and, in some cases, has adverse effects on soil properties.

As freshwater resources become more fully exploited there is an ever-growing need to make better use of saline groundwaters – both those created by irrigation and those from natural aquifers. In the last half-century valuable research work has been done by the U.S. Department of Agriculture. Initially this work was based on studies of arid lands within the U.S. but later it became extended to overseas countries. The results of this and other work led to the adoption of standards for the use of saline and sodic waters. The now well known indicators adopted as a measure of plant tolerance are total soluble salts (t.s.s.) and the electrical conductivity (e.c.) of soil-saturation extract for salinity, and the sodium adsorption ratio (s.a.r.) for alkali hazard. Other indicators were developed for alkali hazard, such as the residual sodium carbonate (r.s.c.); exchangeable sodium percentage (e.s.p.). The limiting values vary for soil and crop types but are generally 8–12 for s.a.r., 5 for r.s.c., $1500/10^6$ for t.s.s. and 3 mS† cm^{-1} for e.c. However, it has been found that there is scope for considerable relaxation of these limits if certain management procedures are followed, and in particular if good land drainage can be assured. Furthermore, waters of high salinity, say $3000/10^6$, can be mixed with fresh water and used without undue loss of crop yield.

There is also evidence that under certain conditions drip irrigation and short-interval sprinklers can make better use of saline waters than the conventional methods. Certainly, the design and operation of irrigation systems has a considerable impact on the distribution of soil salinity within the root zones.

Modern methods of mathematical modelling are proving to be useful tools in designing the optimum systems that will give the more favourable combinations of crops and watering amounts and frequency under saline conditions.

Future research, both theoretical and empirical, needs to be undertaken to obtain a better understanding of the influence of the irrigation process in alleviating the adverse effects of water salinity. In particular there is a need for more applied research because the suitability of saline water for crop production depends more on water management, quality of soils, and crop husbandry than on the quality of the water itself. At Tatura in Australia research is being done on the use of groundwater with $3000/10^6$ t.s.s. 4.6 mS cm^{-1} e.c. and 17 s.a.r. (Cornish 1983).

In the more distant future it is possible that genetic work will lead to more salt-tolerant plant species, particularly cereals.

Sea water

At the extreme end of the scale of salinity of water used for irrigation the Russians have experimented with water from the Baltic, Azov and Caspian seas. For the Caspian, with a salt content of 14000 mg l^{-1}, good results were obtained with tree crops (tamarisk, pomegranite and pine). Mixed with fresh water, it has been used for a range of crops including cereals, alfalfa and cabbage (Bekhbudov *et al.* 1984).

† $1\ S = 1\ \Omega^{-1} = 1\ AV^{-1}$.

It is unlikely that much progress will be made in the use of sea water for irrigation in the near future, except in a few specific locations such as the Caspian where the salinity is less severe than for most sea waters. There are also opportunities to use sea water mixed with fresh water in certain arid-zone countries but the applications are more likely to be for parks and ornamental trees than for food crops.

Sewage effluent

The use of sewage effluent for irrigation is expanding and can be expected to make big advances as the quantity of effluent from urban conurbations becomes greater (see table 5) and where sources of fresh water become fully exploited. (Pescod & Alka 1984.)

TABLE 5. PROJECTED EFFLUENT IN A.D. 2000 FROM SELECTED CITIES

(Source: Pescod *et al.* 1984*a*.)

city	effluent/(Mm^3 a^{-1})
Mexico City	2600
São Paulo	2200
Cairo	1100
Addis Ababa	500

The demand for the re-use of effluent is most significant in the desert or semi-desert climates of the Middle East, southern and northern Africa, and the desert regions of Asia. In addition there is a need to give more attention to the re-use of sewage effluents in many small island countries, such as Mauritius, where demands are beginning to outstrip water resources.

In some countries, including the U.S.A., Israel, and France, irrigation has been used as the final process of effluent treatment. In Israel this objective is essentially linked with the need to conserve scarce water resources. In France, apart from the value of irrigation as a method of effluent treatment, there is the further objective to make use of nutrients in effluents that are beneficial to agriculture. On the other hand, effluents contain various salts and other impurities than can be harmful to plants and soil. More importantly, effluents contain bacteria which can be a health hazard to humans if project management is not of a high order.

The more successful use of effluent has been on forage crops where bacteriological decontamination is affected by weathering. In contrast, corn has proved an unsatisfactory crop in Canada because faecal coliforms survive in the shelter of the leaf sheaths and husks (Jame *et al.* 1984).

Salinity of effluents produces some diminution of yield which can be controlled with adequate allowance for leaching. Furthermore, the drawback of salinity is likely to be offset by the nutrient value to the plant. In trials in Brunswick, Germany, it has been estimated that with an annual application of 300 mm of effluent the quantities of nutrients applied per hectare are 200 kg nitrogen, 64 kg phosphorus, and 45 kg potassium.

In a project in Canada, up to 150 kg ha^{-1} is added to the nitrogen budget in the effluent (Jame *et al.* 1984*b*).

In the use of sewage effluents there is a need for location-specific research because results depend on the treatment process of the effluent and on its final composition and on soils and climate. Treatment objectives must take into account the long-term effects of applying the effluent to the soil in the production of a range of desirable crops (Pescod & Alka 1984).

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4. Control of bilharzia

Wherever irrigation systems have been constructed in developing countries, bilharzia has followed. In the areas of long traditional irrigation such as Egypt, bilharzia is believed to have existed in 1000 B.C. In the new irrigation systems constructed this century, such as the Gezira of the Sudan, half the resident population had become infected by 1970 and among schoolchildren the incidence of the disease was as high as 80%. However, much progress has been made since 1970 through the successful introduction of highly effective anti-shistosomal drugs combined with other measures such as the focal application of molluscicides and some environmental engineering.

Mass chemotherapy has been shown to have remarkable effects. In one case in the Sudan a survey in three villages showed a 50% prevalence of intestinal infection before treatment. At the six-month post-treatment stage the prevalence had been reduced to 14%, and after twelve months to 10% (Gadal 1984). Mass chemotherapy, with its spectacular immediate effects, is not likely to provide a long-term solution. Ultimately improvements in sanitation are essential to provide more permanent protection. The immediate priorities are to pursue all available means of control in a manner that is most cost-effective both in the short- and longer term.

5. Land drainage

Distribution of drainage in the world

In contrast to irrigation, the greater part of the drained areas of the world are in developed countries, as may be seen from table 6, and in rain-cropped regions. More recently, the waterlogging and salinity that has come about in the older irrigation systems has given rise to a new and urgent need to improve drainage in vast areas in the Middle East, the Nile Delta, Indonesia, the Indo-Gangetic plains, Japan, and many other countries with traditional irrigation.

Table 6. Drained and flood-protected areas in the world

region	area/Mha
Europe	29
Asia	50
Africa	1
North America	52
South America	10
Australia and Pacific	2

Types of drainage

Agricultural drainage may be broadly divided into two categories:

(i) surface drainage to dispose of runoff and to prevent prolonged flooding of crops;

(ii) subsurface drainage to prevent waterlogging and salinity in the root zone.

The discussion in this paper is confined to the second category, for which the general term 'land drainage' will be used. It is this form of drainage which represents the great need of the regions cited above.

Land drainage is accomplished by two main methods:

(*a*) *Horizontal* drains – such as open ditches, tiles, moles, subsoiling and perforated plastic pipes;

(*b*) *Vertical* drainage, provided by tube-wells.

Horizontal drainage

Horizontal drainage has made enormous progress in recent years. The old conventional methods of deep open trenches or buried clay or cement tiles are not suitable for application in large parts of the world. The open trenches are too wasteful of land resources. The clay and cement tiles are expensive materials in most countries and costly to handle. Although clay tiles still have application in some humid zones where there are extensive areas of shallow residual soils, they are costly to lay in the alluvial plains of the traditional irrigated areas of the world where deep drain settings are technically feasible and economically preferable.

In the last decade open ditches and clay or cement tiles have given way to plastic perforated corrugated pipe for lateral lines in a drainage system. Furthermore, trenchless laying machines have been introduced. They operate very successfully in most conditions, but trenchless machines have not yet been adapted for heavy soil conditions owing to shearing and compacting effects which create impermeable conditions immediately around the plastic pipes.

Regardless of whether trenchers or trenchless machines are adopted, the dramatic advance in horizontal land drainage is the use of powerful deep-drainage equipment which is capable of operating at higher speed and greater depths than the older trenchers.

Vertical drainage

Tube-well drainage is mainly applicable to irrigated areas where there is a freshwater aquifer and the drainage effluent can be used to supplement the surface water supplies. It is for this reason that tube-well drainage has found wide application in Pakistan and in northern India. Although operated successfully by the private sector, tube-wells in the public sector have given rise to problems, both technical and managerial. Among the technical problems have been encrustation and corrosion of the screens, instability of power supplies and contamination of the freshwater inflows by 'up-welling' from deeper saline layers. Most of these technical problems are being overcome but there remain serious operational problems which relate to the subject of irrigation management discussed earlier.

Tube-well drainage is also used in those saline groundwater areas wherever aquifer characteristics provide high-yielding wells. The problems with this kind of drainage are both economic and technical. As with horizontal drainage in saline areas, the main technical problem is the disposal of effluent. With careful management the effluent can be used for irrigation on medium-textured soils, provided that the total soluble salts (t.s.s.) do not exceed *ca.* $1000–2000/10^6$, the s.a.r. is less than *ca.* 10 and the r.s.c. less than 3, depending on soils and water management. For water with t.s.s. up to about $2500/10^6$, effluents have been successfully mixed with fresh water for irrigation use given suitable facilities to perform the mixing and distribution operations. In sandy soils, effluent of even higher salt content can be used with salt-tolerant crops and good management.

The problem of high cost of land drainage for developing countries

Despite these important advances in land drainage methods, the cost remains high when applied to the agro-economics of many developing countries. The general level of land drainage cost is between U.S. $1000 and U.S. $2000 ha^{-1} for horizontal systems, and much more for vertical systems. In Europe, Japan, the U.S.A., or Egypt, such costs can be justified on economic if not on financial grounds, simply because crop yields are high. In situations where cereal yields are 6–8 tonnes per hectare, a 10% increase in yield as a result of improved drainage brings about a sufficient return on investment. In developing countries where cereal yields are no more than 2–3 tonnes per hectare the incremental production is too small, even with an average of $1\frac{1}{2}$ crops a year, to provide an acceptable economic return. For the present, drainage in these situations can only be justified on social grounds. This merely underlines the need for continued efforts to develop even lower cost drainage methods in the future.

Approach towards low-cost drainage

Any approach towards lower cost drainage will take two forms. One is to develop lower cost methods of construction and the other is to find methods of irrigation and land management that are less demanding to drainage requirements.

The recent development in crop husbandry that is likely to have most effect on drainage needs is the advent of minimum-till techniques. In developed countries the land has long been compacted and pummelled with heavy machinery that has reduced the permeability of the soil and has damaged existing drainage systems. Minimum till should therefore lead to a better state of natural drainage, which should reduce the amount of artificial drainage required. Changes in cropping patterns in humid zones could also reduce drainage demands, for example, the production of pastures in place of sugar beet.

In the arid and semi-arid irrigated zones of the world minimum-till practices are also of value, as may be seen (for example) in rice production in Australia.

A greater impact in the reduction of land drainage requirements is likely to be in improved irrigation application methods either through better water management, as already discussed, or through modern methods of water application. In the western desert areas of Egypt it has been shown that areas served by centre-pivot sprinkler equipment have a much lower tendency to waterlogging than areas with traditional surface irrigation. Drip irrigation, either above or below ground, and microsprinklers, should lead to further reduction in drainage needs and warrants further research and development. In some situations, lower drainage requirements might offset the higher cost of drip and sprinkler installations.

Topics for research and development in drainage

The aspects of land drainage that call for further research and development are summarized as follows.

(i) Improved methods for the installation of horizontal drainage in difficult soils such as shifting sands and heavy clays.

(ii) Lower cost methods of constructing collector drains including the use of plastic pipes of large diameter and trenchless methods.

(iii) Low-energy systems for drainage pumping.

(iv) Effect on drainage requirements of improved water management practices and of drip and sprinkler application methods.

(v) Further development of integral envelopes on perforated pipes as a substitute for conventional gravel envelopes.

(vi) Further development of shallow (skimming) wells for saline groundwater areas.

(vii) Integration of surface and groundwaters with mixing to dilute saline groundwaters with automatic controls.

6. Conclusions

There is a need to promote irrigation and drainage research on an international scale with strong support from the developed countries. The sector is wide and research is called for in many areas, of which some have been described in this paper, ranging from project management to detailed technical problems. In agronomy, the C.G.I.A.R.-supported research establishments have in recent years demonstrated the high returns that are obtainable from location-specific research aimed at areas of large-scale production where marginal benefits become vast in absolute terms. Irrigation alone contributes about 30% to world food production, but much of it with poor efficiency and low crop yields. The scope for increases in productivity are large indeed, if only more success can be achieved in the application of innovations and improved technologies.

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