Land reclamation and water management

ILRI Publication 27

Land reclamation and water management

Developments, Problems and Challenges
A collection of articles published at the occasion of ILRI's silver jubilee (1955–1980)

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Preface

On the 13th of September 1980 the International Institute for Land Reclamation and Improvement commemorated its Silver Jubilee.

The Institute owes its existence to the great flood that struck The Netherlands in February 1953. At that time the country received offers of help from all over the world. One of these offers was financial aid from the W. K. Kellogg Foundation of Battle Creek, Michigan, U.S.A.

The Dutch authorities decided to use the aid offered by the Kellogg Foundation to found an institute. This decision was based on the consideration that The Netherlands, with its centuries of experience in battling against the water, possessed enormous expertise that could be passed on to benefit other countries. The major task of the institute would be to collect and disseminate knowledge in the fields of land reclamation and improvement. The institute would be a nonprofit organization under the Ministry of Agriculture and Fisheries and would be located in Wageningen because other institutions working in fields closely allied to land reclamation and improvement were already established in that town.

And so, on the 13th of September 1955, the International Institute for Land Reclamation and Improvement came into being.

In the ensuing 25 years, the Institute's major task has remained the same, although in 1971 its statutes were altered to direct the activities of the Institute more clearly to meeting the needs of the world's developing countries.

The increasing amounts of funds made available in the 1970's for overseas development work has left an indelible mark upon the Institute. Its advisory services, rendered within the context of the Dutch bilateral programs of technical cooperation, has increased to such an extent that the Deparment of Development Cooperation of the Ministry of Foreign Affairs now contributes 50 per cent of the Institute's budget.

To mark its Silver Jubilee, the Institute decided to issue a special publication – not one summarizing the Institute's history, but one focusing on the activities in which it is involved: the improvement of land and water use for agriculture, with emphasis on the developing countries.

By drawing attention to what has been achieved in these fields over the last 25 years and by pointing out the problems that still remain to be solved, it was felt that such a book would be of interest to a wider public than one merely reminiscing about what is, after all, the Institute's brief past.

Most of the articles have been written by the Institute's own specialist staff members, and one or two with the collaboration of outside specialists. These articles certainly do not claim to cover all aspects of the complicated process of land and water development in the Third World. They do, however, reflect some of the elements on which the Institute, as part of its statutory task, concentrates its efforts.

F. E. Schulze, Director

Abstracts

Land and water development in the Third World

F. E. Schulze and J. M. van Staveren

Mention is made of successive development approaches and their impact on the use of land and water resources. Estimates of these resources and factors affecting their use are discussed. Agricultural growth targets for developing countries as set in various development strategies are reviewed. The two ways of realizing these targets, i.e. by expanding the cultivated area (horizontal expansion) and raising production on already cultivated land (vertical expansion), are treated extensively, as are the tremendous world-wide efforts they will require. Finally attention is drawn to a number of other factors that affect the development process and to the need to strike a proper balance between the sometimes conflicting goals of a broader based development and the compelling need to raise food production.

From soil survey interpretation to land evaluation

K. J. Beek

The increasing and competitive demand for land both for agricultural production and for other purposes requires that decisions be made on the most beneficial use of limited land resources. After a short historical review of land evaluation, three well-known systems are discussed: the U.S. Dept. of Agriculture's Land Capability System, the U.S. Bureau of Reclamation's Classification for Irrigated Agriculture, and FAO's Framework for Land Evaluation.

Problem soils: their reclamation and management

K. J. Beek, W. A. Blokhuis, N. van Breemen, R. Brinkman, P. M. Driessen and L. J. Pons

Vast areas of problem soils exist in the world. Discussed in this article are vertisols, peat soils, acid sulphate soils, planosols, saline and sodic soils and fine-textured alluvial soils, none of which can be used properly without moisture control and water management. For each of these soils, their properties, problems, present land use, and possibilities after reclamation and improvement are described and their world-wide distribution in tables and maps is given. Some of the lessons learned during the last decades and some of the local solutions to the use of these soils are mentioned.

Groundwater resources management research

N. A. de Ridder

Groundwater resources offer great prospects for development to meet the world's growing demand for water. Three concepts of groundwater resources management are reviewed. Attention is drawn to contaminant transport in groundwater systems and to salt water intrusion into fresh-water aquifers. In the complex problem of managing groundwater resources, models of some sort are of great help. The most important models are discussed. Two powerful techniques, the finite differences method and the finite element method, are dealt with more extensively. Model calibration is necessary if the predictions are to have a meaning.

Methods and models in surface water hydrology

J. Boonstra

The problem of matching society's demand for water with the availability of water in nature involves various disciplines, one of which is water resources engineering. The role of hydrology in water resources engineering is described, and an explanation is given of how a hydrologist arrives at his design discharge. A review is made of the many methods and models the hydrologist has at his disposal for the quantitative assessment of flood and low flows. A distinction is made between deterministic and statistical methods. Deterministic methods are subdivided into empirical methods and conceptual models, and statistical methods into probabilistic methods and stochastic models.

Developments in planning of irrigation projects

M. Jurriëns and M. G. Bos

The importance of irrigation in the developing countries and the expansion of the area under irrigation are discussed. Sprinkler and drip irrigation are compared with surface irrigation methods, with consideration given to labour requirements, energy consumption, the efficiency of water use, and costs. Improvements in surface application methods are discussed. Several aspects of the conveyance and distribution systems, such as operation and maintenance, efficiencies, and terminal facilities, are reviewed. Some thoughts are given to the performance of irrigation projects in relation to the necessary improvements in the planning and design of the schemes.

Rice cultivation and water control

J. de Wolf

Throughout vast areas of the less well-fed world, rice provides much of the population's total calorie and protein intake. Water, and consequently irrigation, plays an important role in rice cultivation. Attention is drawn to the farmer within an irrigation scheme, to the tertiary unit, and to factors to be considered in on-farm design for water control. Technical issues involve decisions on water distribution, on the magnitude of the irrigation module, and on the tertiary unit size. Also discussed is the desired degree of intensity in irrigation scheme rehabilitation.

Factors affecting the viability of smallholders' irrigation

L. F. Kortenhorst

The introduction of irrigation into areas where irrigation is not a traditional practice has been receiving high priority in recent years. Irrigation schemes in such areas have been found to contribute little to rural development. A major cause of failure is an overall lack of viability of the project design itself. It is explained that irrigation is a radical intervention in existing farming systems. Some constraints against the successful introduction of irrigation are discussed: culture and tradition, felt needs, skills and knowledge, land tenure, land area, land suitability, water, climate, human health, labour, means, markets, crop health, and risks.

Crop response to water under irrigated conditions

P. J. Slabbers

In the search for ways of raising food production under irrigation, a central theme is the study of soil-water-plant relations. A large majority of the work reported concerns methods with which to estimate 'potential evapotranspiration'. These methods are reviewed. Then a shift away from this philosophy is noted, along with an acceptance of 'deficit' irrigation and thus of methods to estimate 'actual evapotranspiration'. Models describing the effect of water availability on crop yield are reviewed and their relevance for application in developing countries is discussed.

The use of saline water for irrigation

J. W. van Hoorn and R. van Aart

Arid and semi-arid countries are facing the exhaustion of their water resources and are being forced to use poor quality water for irrigated agriculture. The result is often disastrous as extensive productive regions become salinized. In determining the criterion for the suitability of the water for irrigation, the following factors are considered: the quality of the water, its total salt content and chemical composition; the structure and permeability of the soil; the climate, especially evaporation, rainfall, and temperature; the crop, yield depression in relation to salt content, salt tolerance; the quantity of leaching water; the irrigation and drainage conditions; and the management practices of the farmer.

The study of effects of drainage on agriculture

R. J. Oosterbaan

In view of the world's vast need for drainage, the data base on the effects of drainage on soil, plant, hydrology, and agricultural practices needs to be expanded. The lines along which past research efforts have developed are reviewed. Results of research in field experiments, where the elements of nature cannot be controlled, often conflict with results found under controlled conditions. The need for monitoring programs and economic evaluations of drainage projects after their implementation is stressed.

Developments in subsurface drainage techniques

G. Zijlstra and C. L. van Someren

After a short historical review of drainage techniques, the development of the trencher and trenchless drainage machines (or drain plough) is discussed. Dealt with are: depth and grade control, the drain pipes (formerly of clay or concrete and now of plastic), the envelope materials used, and the handling of these materials. Attention is drawn to a new technique, 'horizontal well pointing', which can overcome the problems met in collector pipe laying.

Scientific information: transfer and retrieval

G. Naber

Because of the great quantity of information being produced and the variety of ways in which it is published, the scientist faces a formidable task in keeping track of it all. In an attempt to lighten his task, the structure of scientific information is described, together with the regulatory mechanisms that control the flow of publications. Techniques to gather information are reviewed, with particular attention to on-line information retrieval from computer-stored bibliographical records.

Land and water development in the Third World

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Successive development approaches

The approaches to land and water development have undergone many changes in the course of time. Some of these changes came about because of changing insights into the use of natural resources, others because of new insights into the problems of underdevelopment that exists in so many countries.

Before World War II, land and water development in industrialized countries was marked by:

- The growing realization that the use of natural resources for economic development was only justified if at the same time care was taken to conserve these resources. What primarily led to this realization was the enormous damage brought by erosion, a dramatic example of which is the 'dust bowl' in the U.S.A. in 1934.
- The concept of multi-purpose projects that regarded a river basin as a unit. Within this unit, water resources were developed under the keywords: irrigation, flood control, navigation, and power generation.

The end of World War II marked the beginning of decolonization. The first post-colonial period was characterized by a great optimism – by a belief in the equality of all nations and a belief in their universal potential for economic growth. Admittedly, some countries (the developed ones) were more advanced; others (the developing countries) less; but policy was directed towards catching up on arrears. The optimism that marked this period sprang from an implicit faith in an evolutionary, self-strengthening development process. (In conformity with the use of these terms in U.N. publications, *developing countries* are the 90 countries under development market economies, located in the four regions of Africa, Latin America, Near East, Asia (excluding China) and the Far East, and *developed countries* are the countries under developed market economies, and the countries of Eastern Europe and the U.S.S.R. under centrally planned economies.)

When, in spite of these high-pitched expectations, the developing countries did not magically achieve overnight development, the blame was successively placed on: the backwardness of their industry, their lack of infrastructure, their too rapid population growth, and the ill-adapted structure of their society.

Much of the land and water development in this post-war era was focussed on large-scale irrigation projects. These were implemented in the belief that once infrastructural works had eliminated the constraint of water shortage, further development would automatically follow. But here too one soon noted a shift in emphasis: the initial concern for 'water' as the specific constraint was promptly followed by a search for other reasons to explain why development lagged behind expectations. And so began an increasing interest in soil conditions and land classification in their relation to irrigation and drainage. The approach of eliminating one or more bottlenecks continued.

At the beginning of the sixties, other ideas entered the picture. These expressed that the blame lay not so much on the technical problems within the development process, but more on other factors – factors that were inherent to developing countries. Mentioned as examples were that the machinery of government did not function properly and that there were gross inequalities in the distribution of property and income. A different adapted approach was advocated, one that would:

- devote more thought to the agro-technical, economic, and social factors that affect the (small) farmer's production;
- regard the design and construction of tertiary unit facilities as an essential part of a water management project and not leave these matters exclusively to the farmers, who usually lack both the means and the knowledge to handle them;
- institute pilot projects so that experience could be acquired and a better insight gained into local problems before large-scale implementation;
- accept the complexity of the planning process and adopt a multidisciplinary, integrated approach.

In the seventies, the developing countries sounded a note of their own, with insistence upon self-reliance (Non-Aligned Countries' Conferences in Lusaka 1970 and Georgetown 1972). With faith in their own powers, they would pursue a development policy aimed at creating their own social and economic communities. This concept was soon followed by another; that of basic needs, which emphasized the urgency of providing all people with food, housing, education, and health care. A logical consequence of the basic needs approach was an increased concern for the plight of the poorest elements of society, whereby high priority was given to the issues of employment for all and an equitable income distribution.

As both these concepts – that of self-reliance and basic needs – still feature prominently in discussions, we cannot say what ultimate effect they will have on national development plans or on bilateral aid programs. However, they include obvious desiderata that are most certainly influencing trends in land and water development. These are:

- a growing interest in, and a consequent larger flow of funds to, small-scale development;
- more consideration being given to appropriate technologies, low costs, and labour-intensive methods;
- the active involvement of the local population in planning and implementing a project and in its subsequent operation and maintenance;
- the selection of land and water development projects on broadly-based development goals of income distribution, social services, employment promotion, etc., rather than on purely technical and economic criteria.

This fragmentary account shows how turbulent the process of development is. Within the space of a quarter of a century, changing insights into economics and techniques and changing socio-political attitudes have all had their repercussions on development. One could regard the process as the inevitable pains that accompany growth, and, of course, no experience could ever be acquired without trial and error, even though such exercises are expensive in terms of time and money. But it would be naïve to imagine that the process is nearing any definitive form. Instead, one can expect a constant flux of impulses (from within and without) – all calling for adjustments in national and international policies. The uncertain future of the world's energy supplies is a case in point.

One obvious conclusion is that any long-term planning should consist of a series of programs that have broad aims and an in-built flexibility that allows them to be adapted to new insights and events. Within this flexible framework, a continuous stream of small projects can be implemented, all designed to yield their socio-economic benefits with a minimum of delay and each drawing upon the experience gained in preceding projects.

Land resources versus their threats

In the course of time, various authors have produced appraisals of the magnitude of potentially arable land. Some of the more recent appraisals are presented in Table 1.

From a comparison of the potential areas with those at present cultivated, one could get the impression that there is still ample land for development. But, as will be explained later, it is feared that the costs of developing much of this land will be prohibitive.

A breakdown of the figures per continent shows that the reserves are principally found in:

- Latin America and tropical Africa, under developing market economies
- the Asiatic parts of the U.S.S.R, under a centrally planned economy
- North America and Australia, under developed market economies.

Table 1.
Estimated potential arable land, in million hectares.

Authors	World total	Developing countries only
Kellogg and Orvedal (1969)	3,200	
Kovda (1974)	5,000	
Buringh (1975)	3,400	1,800
Revelle (1976)	3,150	1,575
FAO (1979)		1,774
Presently cultivated (1975)	1,400	730

In their estimates of potential arable land, the authors cited have disregarded possible losses of land. Throughout history, however, irreparable damage has been done to land through drastic deforestation (for fuel, building materials, etc.) and the over-hasty reclamation of marginal soils. The total area of destroyed and degraded soils that were once biologically productive is estimated at 2.000 million hectares, thus more than the world's present-day cultivated area! The main loss took place in the last 100 to 200 years (BENNETT 1939, KOVDA 1977).

Today's generation recognizes the dangers, and is in principle familiar with the procedures of curbing erosion and conserving the land. Nevertheless, the process of land degradation continues – often as a side-effect of land development, and especially at places where population pressure, overgrazing, and mismanagement have upset the natural equilibrium between soils and vegetation. KOVDA (1977) estimates that worldwide a total of 5 to 7 million hectares of land are lost to agriculture each year through water and wind erosion, salinization, urbanization, rural settlements, road systems, industrial enterprises, mines, oil fields, and soil contamination.

At least half of the yearly loss of land (or approximately 3 million hectares) is attributable to the conversion of crop land to non-agricultural uses (BROWN 1978). As this encroachment is proceeding in the same proportion as the growth in population, this negative component can be expected to double in the coming decades, with most of it concentrated in the developing countries. Other negative effects of this conversion are that the quality of the newly-won land will be lower than that of the converted land (and the costs therefore higher) and that it will in general be farther removed from the existing population centres.

Apart from the loss of crop land through its conversion to other uses, there is every reason to fear that the natural soil fertility in areas sensitive to erosion – and these constitute a far from negligible part of the arable area – will decline as the top layer of soil is gradually removed by wind and water. This creeping process of gradually declining yields can ultimately lead to the abandonment of the land. No reliable mondial figures are available on the extent of these processes. Their effects are often blurred, and they can be temporarily compensated for by increased fertilizer applications. But recent figures from certain countries and regions (e.g. the Sahel) present anything but a cheerful picture.

We even venture to cast doubt on the statistical figures that governments supply regarding their areas of arable land. Do they, we wonder, in their

figures, properly take into account the land that is lost through degradation, urbanization, etc.?
The further expansion of arable land will take place on soils that are even more sensitive to erosion than the present arable land. What is more, the future areas are now under forest or other vegetation and thus fulfil a function in maintaining ecological equilibrium. Gross exploitation of natural forests, as is now taking place in Asia and Latin America (respectively 8 and 5–10 million hectares a year) will, if allowed to proceed unchecked, form a serious threat to ecological equilibrium within two or three decades.
Another problem, for which one must be increasingly on the alert, is the dispersion of toxic substances (fertilizers, biocides, etc.) through the air and through waterways. Industrial countries have already suffered damage from these pollutants. Their widespread use in developing countries will call for great ecological awareness on the part of those responsible for research and development, both in governmental and industrial circles (de BIVORT 1975).
It will be clear that strenuous efforts must be made to prevent any further losses of land. Reforestation must provide degraded land with a new vegetational cover, and a halt must be called to further upsets in the ecological equilibrium. Nevertheless, none of this will be achieved without a heavy flow of finances, a large measure of legislative action, and intensive programs to make everyone involved aware of the gravity of the situation.

Water resources

Few estimates have been made of the available quantities of river flow, although it is generally accepted that the total annual flow is between 40,000 and 47,000 km^3 Part of this, however, concerns flood flows, which cannot be regulated economically and are therefore unusable. LVOVITCH (1973) estimates flood flows to be 64 per cent of the total, so that in principle 36 per cent of the river flow, or some 14,000 km^3 a year, is available.
This appears to be quite a large quantity in comparison with the present total quantity used (roughly 3000–3500 km^3). But one must not forget the variability in space and time: the water is not always available in the right place or at the right moment. It is therefore not surprising that groundwater is nowadays receiving widespread attention. The article by de Ridder makes clear that a great potential exists for groundwater. But here too one meets problems, in the sense that in many places where groundwater is needed it is not always of good quality or it cannot be exploited economically.
Estimates of the present – let alone the future – water use for irrigation are characterized by a great diversity, not only because the quantities required per project differ owing to variations in evaporation, effective precipitation, etc., but also because of variations in the irrigation losses, which ultimately determine the gross demand. One must therefore not be too surprised at the widely divergent estimates of the present and future water use for irrigation as shown in Table 2. FAO (1974) reckons with a gross demand (crop use and irrigation losses) of 15,000 m^3 per hectare per year for rice and 7,000 m^3 for other crops. At first glance these figures seem rather low, but they are not improbable when one considers that they are average values which include the low water requirements for supplementary irrigation.
Estimates of the water needs for non-irrigation purposes are even more difficult to make. To give an idea of the order of magnitude, however, in comparison with the 2,500 km^3 used for irri-

Table 2.
Estimated world-wide water use for irrigation.

Source		Present use		Future use	
		(km^3)	year	(km^3)	year
Doxiades	1967	1325	1960	3120	1990
FAO	1971	1400	1965	2800	2000
Lvovitch	1973	2300	1965	–	–
FAO	1974	2570	1970	–	–
FAO	1977	1250[1]	1974	1700[1]	1990

[1] Developing countries only.

gation, industry currently uses 500 km^3 while another 200 km^3 is used for various other purposes, including domestic water supplies. It is obvious that under the present circumstances, irrigation, which accounts for roughly 80 per cent of all water now used, is by far the greatest consumer and is likely to remain so for some time to come.

But we must reiterate that these figures are only very rough estimates and claim to do little more than indicate an order of magnitude. The future water use depends on such a great many factors, including the future world economy, that any estimate of its quantity can be regarded as no more than an educated guess. Certain factors, however, seem to indicate that by the year 2000 the world will be using some 6,000 to 7,000 km^3 a year, which comes close to half the earlier-mentioned total available quantity of river flow: 14,000 km^3. A much-heard cry nowadays concerns the need to practise greater economies in the use of water. Forming part of this trend are the efforts being made to improve the efficiency of water use in irrigation schemes. Rehabilitating existing schemes and improving on-farm water use are key words in this process. The FAO Committee on Agriculture in its 1979 session rightly called for national and international action programs on these subjects.

There is indeed no real need to argue the case for safeguarding earlier investments and preventing further land degradation by improving and rehabilitating existing schemes, rather than embarking on new schemes. For the planner and designer, this may be a far less glamorous task, but there is no doubt that rehabilitation will offer considerably higher and far more rapid returns on investments than will new projects.

Until now, most of our remarks have been concerned with water quantities, which does not in any way imply that the quality of the water is unimportant. The article by van Aart and van Hoorn discusses the use of saline water for irrigation. Even if theoretically usable, however, saline water requires a highly sophisticated management to prevent the delicate relationship between soil, water, and crop from being disturbed. That such careful management is all too often underrated is clear from the estimates by the United Nations (1977) that approximately 120,000 hectares of irrigated land are annually lost to production.

Irrigation itself is one of the major polluters of water. In a study of the Colorado River, EL ASHRY (1980) showed that 47 per cent of the river's salinity load could be ascribed to natural causes and 45 per cent to irrigation.

The very low efficiency of water use common to irrigation projects – sometimes only 20 to 40 per cent – results in the outflow of huge quantities of unused irrigation water, whose quality often leaves much to be desired. In many countries with a shortage of irrigation water, apart from the efforts being dedicated to raising irrigation efficiencies, the re-use of drainage water has become a central issue. It speaks for itself that the problems faced by management in manipulating both water quantities and water qualities are very complicated indeed.

Agricultural growth targets

The current world population is roughly estimated at 4,200 million (1978 figures), half of whom live in developing countries. A major distinction between the two halves into which the world can thus be divided is the growth rate of their populations: in the developing half a growth rate of 2.6 per cent per annum, and little more than 1 per cent in the developed half (including China). A country's demand for food is closely linked to the size of its population and to their income. The relatively high growth rate in the developing countries generates, at the very least, a proportional growth in their food demand. Any improvement in their income – which, unfortunately, is difficult to realize – drives the food demand even higher. A grim truth is that in the developing countries, approximately 450 million people (more than 20 per cent!) are suffering from severe undernourishment (FAO 1978).

These malnourished people are found mainly in the poorest countries, in the poorest urban popu-

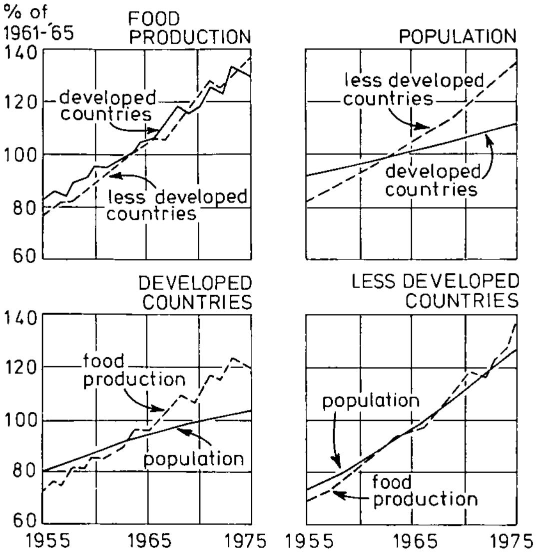

Figure 1.
Food production and population in developed and developing countries (Economic Research Service, U.S. Dept. of Agriculture 1979).

lations, and in rural areas where adverse ecological conditions or other factors have led to widespread unemployment.

The world's food production is indeed growing, but it fluctuates because of weather conditions or natural disasters that constantly upset the balance. The neck-and neck race between food demand and food production is reflected in Figure 1.

The most important aim in food production is to achieve regional self-sufficiency, either per country or per group of countries. The recent trends in self-sufficiency shown in Figure 2, however, reveal an almost unanimous decline.

The question of future food supplies thus remains an urgent and challenging issue for which the answers must be sought in the developing countries themselves. Shipments of food from the developed half of the world – except incidentally in emergencies – would not lessen the predicament. Much more than just food supplies are at stake. Between 60 and 70 per cent of the people in developing countries depend on agriculture for their livelihood. The only way they can obtain the sorely needed increase in their income is to raise production, with room to market high-quality crops.

The target set for the developing countries in the Second U.N. Development Decade – DD 2 – (1970–1980) was an average annual increase in agricultural production of 4 per cent. This target was reaffirmed by the U.N. World Food Conference of 1974. For years now, however, the actual increase has not exceeded 2.6 per cent, which is just sufficient to keep pace with the population growth and does nothing to alleviate undernourishment or to improve incomes.

In preparing the strategy for DD 3 (1980–1990), the magic figure of 4 per cent has once again been set. What this means in terms of accelerated agricultural growth and the development of land and water resources in shown in Table 3.

In principle, production can be raised in two ways: by expanding the area of cultivated land (horizontal expansion) and by intensifying production on already cultivated land through irrigation, improved seeds, etc. (vertical expansion). From 1963 to 1975, roughly one-third (or 0.8 per cent) of the annual increase in production was realized by horizontal expansion and roughly two-thirds (or 1.8 per cent) by vertical expansion. To meet the target set for DD 3, these two expansions will have to accelerate by half as much again, which means, maintaining the same ratio, an annual increase of 1.2 and 2.6 per cent respectively.

The targets set in *Agriculture: toward 2000* (FAO 1979) are 3.6 per cent per annum for crop production and 4.7 per cent per annum for livestock. As livestock constitutes 20 per cent of the gross value of agricultural production, the mean target growth rate is some 3.8 per cent per annum. According to this study, 28 per cent of the additional crop production will result from horizontal expansion and 72 per cent from vertical expansion. For the countries concerned, this will mean vigorous extra efforts. Let us now examine the possibilities and the constraints of such a meritorious but ambitious program.

Vertical expansion

Crop yields in the developing countries are lower than those in the developed countries. For instance, the average yields of cereals in the developing countries are between 1100 and 1500 kg per hectare, but are considerably higher in Europe and the U.S.A. These differences are primarily due to differences in levels of farm management and consequent differences in farm inputs.

The importance of various yield-improvement factors, and their cumulative effect, can be seen in Table 4 (see also article by Jurriëns and Bos).

The traditional closed subsistence system adopted in most developing countries does not include the use of fertilizers, which means that not all the land can be cropped each year and that

Table 3.
Growth rates for some selected key figure (90 developing countries).

	Average annual growth from 1963–1975		Target annual growth for 1980–1990	
	in per cent	in million ha	in per cent	in million ha
Gross value of agr. production[1]	2.6		4.0	
Gross value crop production	2.6		3.8	
Arable land	0.8	appr. 6.0	1.2	appr. 10.0
Yield (per ha)	1.8		2.6	
Irrigated area	2.6	appr. 2.2	2.2	appr. 2.5

[1] including livestock.

part of it must lie fallow. Cropping intensity is rarely more than 60 per cent.

With a transition to more modern systems of farm management, cropping intensities could be raised to more than 100 per cent through multiple cropping. Admittedly, this is only possible in areas that have a good rainfall distribution or are irrigated under good water management, but many parts of the tropics and subtropics can satisfy these requirements.

To give an idea of the yields that could be obtained, reference is made to a study by BURINGH, van HEEMST, and STARING (1975). On the basis of climatological data and the rea-

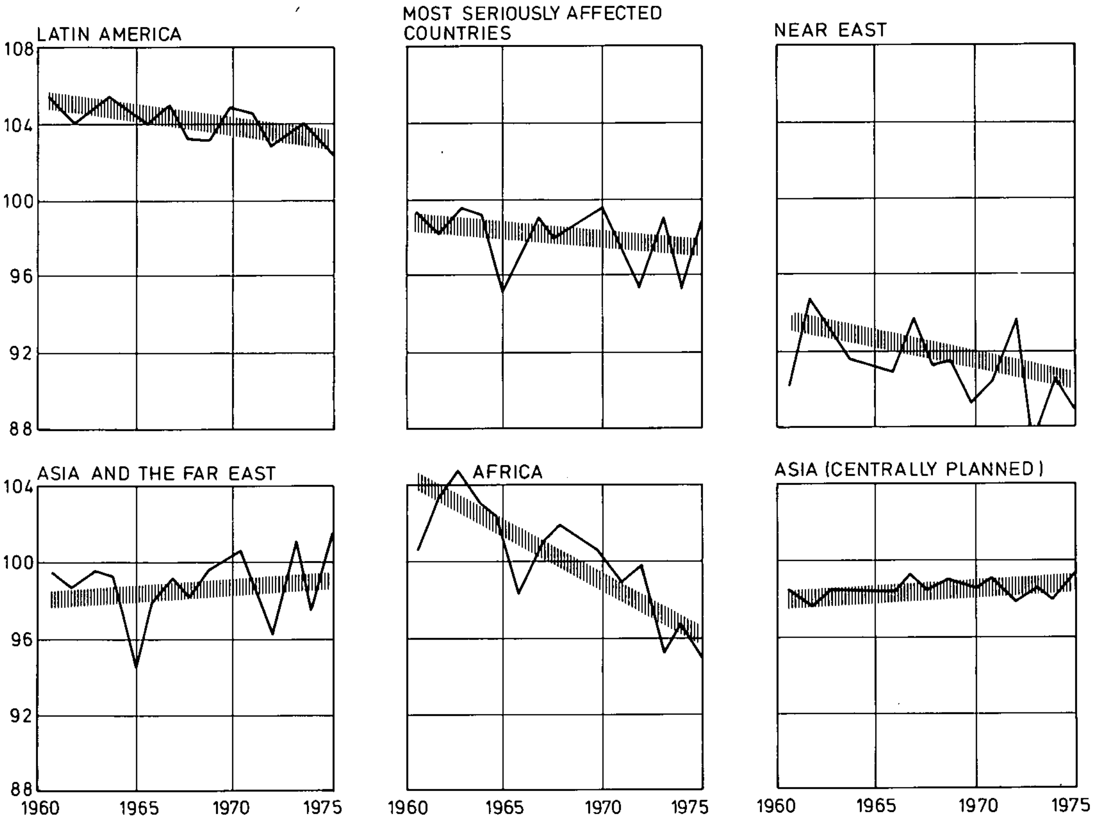

Figure 2.
Trends in self-sufficiency[1].

[1] Only in Asia and the Far East, including the Asian centrally planned economies, is there an upward trend in levels of food self-sufficiency. The situation for all other regions and groupings reflects a steady downward trend, although there have often been sharp year-to-year fluctuations. The most dramatic decline has been in Africa where the self-sufficiency ratio has dropped from a height of 104 in 1963 to about 95 in 1975. The decline in the Near East reflects, in part, the demand for imported food among oil-exporting countries. Only Latin America has been able to sustain a food self-sufficiency ratio above 100, but even there the trend is downward.
(Source: FAO, Ceres. Vol. 12–1)

sonably well-known process of photosynthesis, these authors calculated the theoretical absolute maximum food production, which they expressed in dry matter production per hectare per year for 222 broad soil regions of the world. In their calculations, they assumed that the soils had been brought to optimum condition, that they received fertilizers and other amendments, had an optimum water supply, and that plant diseases did not occur. They used two reduction factors; one where soil conditions would be a limiting factor and one where water deficiency might occur. In this way they arrived at a world-wide average yield of 14 tons per hectare per year, with averages per continent varying from 10 tons in Europe and Australia and 18 tons in South America. In spite of the reduction factors, however, these yields must be regarded as theoretical only. They will never be attained in practice because of economic and organizational limitations. Nevertheless, it is interesting to see how closely these maximum yields are being approached by yields obtained here and there under optimum circumstances (see Table 5).

Table 4.
Assumptions regarding contributions to yield growth from selected yield-improving factors over the period 1965–2000 in the Indus Plain of Pakistan (LIEFTINCK et al. 1969).

		Factor contribution in isolation %	Cumulative yield %	Apparent contribution in combination %
Present yield			100	
Factors	Additional water supplies alone	10	110	10
	Elimination of waterlogging and salinity	10	121	11
	Application of fertilizers	40	169	48
	Disease and pest control	15	195	26
	Improved seed preparation and cultivation practices	20	234	39
	Improved varieties	20	281	47

Table 5.
Observed and calculated maximum yields.

Country	Crop	Actual yield in tons/ha	Calculated max. yield in tons/ha
Philippines	3 rice crops per year	26	28.6
N.W. U.S.A.	wheat	14.5	15–18
Netherlands	wheat	8–9	10.5
Madagascar	2 rice crops per year	16.2	17.7
Senegal	2 rice crops per year	14	16.9
S.W. Finland	winter wheat	6.2	7.2

The study by Buringh et al. shows that the potential production level in tropical and subtropical areas, where most of the Third World countries lie, is significantly higher than that in the temperate zones, which contain the main industrial countries. According to van ITTERSUM (1971) the best farmers ought to be able to reach a production level that lies 25 to 35 per cent below the theoretical maximum. In its 1977 Annual Report, the International Rice Research Institute (IRRI 1978) estimates the practical production potential in the order of 50 per cent of the biological potential. If developing countries could achieve even this level, it would mean crop yields at least five times as high as those obtained at present.

In spite of the many factors that make it impossible to attain the theoretical maximum yields – a phenomenon that has currently become known as the 'yield gap' or the 'potential performance gap' – there is still abundant scope, especially in the Third World, for increased production through vertical expansion.

Horizontal expansion

For agriculture, the factor 'land' is, both literally and figuratively, the basic resource. Within the identified total potential arable area of about 3,400 million hectares, many different soils occur. Throughout the course of history, in the nature of things, the best soils were always the first to be brought under cultivation. The reserves of land that still remain can be regarded as 'inferior', with explicit limitations to their use. Or to put it another way, the cultivation of these soils will mean relatively high reclamation costs and high recurrent costs for their proper management. Of the 3,400 million hectares of potential arable land, more than 1,400 million hectares are at present under cultivation, thus leaving some 2,000 million hectares of potential reserve. This physiographic statement, however, gives expression to highly charged hopes that are far removed from reality.

As the population growth in the developed countries is relatively small (about 1 per cent) and as there is no other urgent economic stimulus to expand agricultural production, it is unlikely that any large-scale development of new land will take place there. The reserves of land in those countries can therefore be regarded as latent.

Further, experience has shown that one must not entertain any great expectations of permanent agriculture in areas at present covered by tropical rain forests. In the Amazon Basin in Brazil, for example, little more than 5 per cent of the land is fertile; as well, the cultivation of annual crops is greatly hampered by plant diseases. Before these areas can be used for basic food crops, an entirely new 'agroforestry' method will have to be developed. Anyway, in the interests of maintaining ecological equilibrium, the area of arable land within this agroforestry structure will have to be kept to a certain minimum, which will be only a small part of the whole.

Under the pressure of population growth in the last decades, vast areas of land in the developing countries have been opened up for cultivation, although not always with success. The costs (primary and recurrent) of reclaiming the land usually far exceed the estimates, while one also finds that current management practices often prove futile in keeping the fragile newly-won land in sustained production.

The investments needed to reclaim new areas will be considerably more than the investments that went into previous reclamations. The study by BURINGH et al. (1975) grouped the yet reclaimable land into classes on the basis of the cost of their development. Table 6, which was compiled from their data, shows the areas and classes per continent.

The table forces the conclusion that, because of the high costs, not more than 200 or 300 million hectares of land in the Third World countries could justifiably be considered for development in the coming decades. (This is apart from some millions of hectares of the lowest cost classes that occur dispersed over extensively exploited agricultural areas).

The margin for expansion thus totals only 25 to 30 per cent of the existing arable land, of which by far the major part lies in Africa and a small part in South America, whereas Asia offers almost no opportunities for further reclamation at a reasonable level of investment. The unfavourable distribution of the land reserves over the continents is clear when one considers that Asia (excluding China) has twice as many inhabitants as Africa and South America together.

Taken all round, and whilst admitting the differences between continents, one should not entertain any great hopes of large-scale expansion of the arable areas in the Third World. In their development planning of the past decades, some

Table 6.
Yet reclaimable land, classified according to investments (Areas in million hectares. Costs in U.S. $[1], 1975 prices) (BURINGH et al. 1975).

	Potential arable land	Already cultivated land	Potential[2] arable land reserve	Classes of development costs in U.S. $ per ha				
				(1) less than 300	(2) 300 to 1500	(3) 1500 to 3000	(4) 3000 to 4500	(5) more than 4500
Africa	711	158	533	–	176	206	162	9
South America	596	77	519	–	31	163	125	200
Asia[3]	887	689	198	–	–	–	82	116
Subtotal	2,194	924	1,270	–	207	369	369	325
Europe[3]	399	211	188	–	–	140	369	325
North America	627	239	388	–	–	351	37	–
Australia	199	32	167	–	–	31	123	13
Subtotal	1,225	482	743	–	–	522	200	21
World	3,419	1,406	2,013	–	207	891	569	346

[1] The costs refer exclusively to works for the reclamation proper: clearing, soil conservation, terracing, levelling, drainage, subsoiling etc. Not included are the costs of infrastructure (roads, waterways, main irrigation works, etc.) or of settlement (housing, service centres, etc.)

[2] The figures for the potential arable land reserves for Africa, South America, and Asia are approximately 20 per cent more than the estimates given in the recent FAO study: *Agriculture: toward 2000* (1979)

[3] The U.S.S.R. area is divided over the European and Asian continents

developing countries have placed great emphasis on new reclamations; the total annual increase has been approximately 6 million hectares. We cannot help wondering, however, why these countries do not shift their planning into the line of vertical expansion, which offers far more opportunities of increasing production than does horizontal expansion.

But here we are merely repeating a recommendation heard at a succession of international conferences.

The current rate of new land development can scarcely keep pace with the losses of land through erosion and other forms of degradation. There is a lack of logic here when one observes the great technical and financial efforts being put into reclaiming new land, while elsewhere land is being lost as a result of neglect or inexpert management. The costs of land conservation and land improvement are only a fraction of those of development. What is more, once land has been rigorously degraded, it can usually be written off as lost for use as future arable land.

Perspective plans

During the last ten years, various U.N. agencies have devised strategies for agriculture and included in those strategies estimates of the investments that would be required to make them succeed. Some of these studies are:

- Indicative world plan for agricultural development, FAO, Rome (1970)
- World food problem – proposals for national and international action, World Food Conference (1974)
- A perspective on the food grain situation in the poorest countries, World Bank (1977)
- Investment and input requirements for accelerating food production by 1990 in low-income countries, International Food Policy Research Institute (IFPRI 1979)
- Investment requirement for food production, U.N. World Food Council (1979)
- Agriculture: towards 2000. A normative scenario, FAO, Rome (1979)

All these studies share one basic consensus: that the growth rate of the gross agricultural production in the developing countries must increase from its historical 2.6 per cent per annum to a new level of approximately 4 per cent.

The contents of the successive strategies reflect the ever-deepening insight into the priorities within the development process. That the cost estimates of each successive strategy are higher than those of the preceding one is not just a matter of inflation; they reveal the growing awareness that alongside costs at project level, there is a need to include other costs as well. FAO's most recent effort, *Agriculture: toward 2000*, for instance, differentiates between:

- Net and gross investments, the difference between them accounting for depreciation charges on existing capital stocks. Those charges may vary considerably per type of investment. On the average the depreciation share of the present package amounts to between 41 and 43 per cent of the gross investments.
- Investments according to OECD's narrow and broad definition. Included in the broad definition but not in the narrow are, for instance, the investments required for the manufacture and maintenance of agricultural inputs, agro-processing industries, infrastructure and transportation, and regional or river development projects.

Let us now take a look at some of the more salient points that emerge from *Agriculture; toward 2000*. This study assesses the implications for the development of agriculture as a whole (including non-food crops and livestock production) and for the 90 developing countries together.

The target set by this perspective plan is that between 1980 and 2000 agricultural production in the 90 developing countries will have to increase at an average rate of 3.8 per cent per annum. The funds needed to hit this target are tremendous, as can be seen in Table 7.

According to the table, to achieve the projected average annual growth rate of 3.8 per cent, the annual investments in agriculture must double in the coming 20 years. The proportion of investments for crop production spent on land development, soil conservation, irrigation and flood control will decrease from approximately 70 per cent in 1980 to 50 per cent in 2000 as far as the net investments are concerned and from 50 to 40

Table 7.
Annual investment requirements for agricultural development in 90 developing countries (amounts in $ 1000 million, 1975 prices).

	1980		1990		2000	
	net	gross	net	gross	net	gross
Crop production	15.4	31.0	22.5	44.6	29.0	59.7
Livestock production	3.5	3.5	6.7	6.7	10.8	10.8
Storage and marketing	2.7	3.9	4.1	5.9	5.3	7.9
Transporting and processing	8.4	14.0	13.1	21.2	16.7	28.3
Total	30.0	52.4	46.4	78.4	61.8	106.7

per cent for the gross investments.

The program scheduled for the land and water investments is broadly in line with the possibilities that have been discussed earlier in this article. Summarizing this program, it incorporates:

- the reclamation of rain-fed arable land at an annual rate that starts at 5 million hectares in 1980 and rises to 10 million hectares by 2000
- soil and water conservation for a total of 190 million hectares to be reached by 2000
- flood control works for the protection of an additional 15 million hectares by 2000
- the development of new irrigation schemes at an annual rate of 2.4 million hectares
- the rehabilitation of 13.4 million hectares of existing irrigation schemes.

The question arises how the required investments are to be financed. There is no doubt that the developing countries will have to mobilize immense new resources to cope with the investments, both within their own borders and outside. The low income countries, in particular, will have to rely heavily on development aid.

The FAO projection is based on the assumption that aid from outside, i.e. from the developed countries, will cover the major part of the foreign exchange component of investments, together with a 10 per cent share of the component of current inputs, as well as the usual contribution of technical aid.

Thus aid from outside will amount to roughly one quarter of the gross investments, or $ 13,000 million in 1980 and $ 27,000 by 2000. When these figures are compared with the 1977 level of $ 4,300, it is obvious what a tremendous increase this will mean in outside aid.

The contribution on the part of the developing countries themselves is in no way a modest one. Indeed, tremendous efforts will be required of them in financing their part of the affair, and most of the funds will have to come from an increase in agricultural production.

The astronomical amounts involved in the projected development of land and water make it clear that financing the programs will be one of the major constraints. It can only be hoped that new international development strategies will find the means to implement these programs, programs that are becoming – literally and figuratively – a matter of life or death!

Other factors of development

In the foregoing analysis of the needs on the one hand and the potentials on the other, the stress lay primarily on the physcial factors of land and water. This may have created the impression that the solution to problems like the world's food situation is purely a matter of making a better and more intensive use of these natural resources. Although nobody will deny that this is indeed one of the requirements, it has been made abundantly clear in practice that a number of other factors, all of a socio-economic nature, play a role of decisive importance. In this article, it is not possible to go into all these factors in detail. Yet we would be failing in our task if we did not mention at least some of them, even if only briefly.

One of the first issues that thrusts itself into the foreground is the question: why, when it has been shown that agricultural production per unit of land in the developing countries could be increased five time over – why then has the annual average increase from 1963 to 1975 been a mere 1.8 per cent? This leads automatically to a second question: what value can we attach to growth targets of 2.6 per cent yield increase per hectare per annum as set, for instance, by FAO in *Agriculture: toward 2000* or for the Third U.N. Development Decade (1980–1990).

If the reader expects well-reasoned answers to these two questions here, he will be disappointed. We could list many factors that are involved in one way or another, but instead we shall restrict ourselves to some general observations.

The first of these concerns the growing cognizance that the failure of development projects and programs in the Third World is primarily due to the lack of proper knowledge of the local situation. The article by Kortenhorst discusses some of the human aspects surrounding the question: why does the farmer act the way he does and why can't he or won't he act otherwise?

In his decision-making, the farmer is influenced by factors that are rooted deep in the total socio-economic context within which he functions. There are actually two sets of factors: one over which the farmer can exert control and which have to do with his pattern of expectations, and the second set of factors which are inherent to his environment and over which he has no control. It is vital that planners have a thorough knowledge of both sets of factors if projects and programs intended to develop the rural areas of the Third World are to succeed. The first step, recognizing the importance of this knowledge, has already been taken. If it is followed by other steps which translate this recognition into action, a moderate measure of optimism for the success of further projects might not be out of place.

For our second observation, we refer to a publication by de WIT and van HEEMST (1976). In this publication, the production increases in a number of countries, expressed in kilograms of grain per hectare per year, are compared in a historical perspective. It appears that in countries that can be classified as developing, the production increase over a great many years is at a level of about 17 kg per ha per year. Expressed as a percentage, this annual increase at a production level of, say, 1500 kg is only slightly above 1 per cent. But, it also appears that as soon as the yield level reaches some 1700 kg, other agricultural techniques are introduced, which causes the annual increase to rise abruptly to 78 kg per ha. This is a 4 per cent rise, and is more than the rate of population growth. So on this matter too, a moderate measure of optimism is justified.

Another issue that warrants discussion is the need to modernize agriculture. By this we do not simply mean improved production methods and better management, but the absolute and dire necessity to modernize in order to meet the world's demand for food.

BURINGH and van HEEMST (1977) calculated that without mechanization, motorization, and the use of fertilizers and biocides, it is utterly out of the question that the world can be provided with sufficient food. Moreover, a system without these measures would, because of the enormous areas of land that would have to be brought under cultivation, mean an unacceptable onslaught on the already fragile ecological equilibrium. Modern agriculture confined to a minimum area would therefore seem to be the only way to maintain ecological equilibrium and at the same time produce enough food.

A further issue that deserves consideration is what are known in economics terminology as 'externalities' and in technical terminology as 'disruptive side effects'. Both these phenomena are closely interwoven with the knowledge that the planner has of the processes in which he intervenes to make them satisfy certain development goals.

An example of disruptive side effects is the occurrence of high watertables and consequent soil salinization that result from irrigation. Such effects can occur if the planner is insufficiently knowledgeable of the natural processes that follow the implementation of a project. In how far they occur because they were deliberately left out of consideration for political or financial reasons, we shall not venture an opinion.

Even more drastic effects can be produced by project externalities. These come into play when the only way the goals of certain projects can be achieved is at the expense of other, wider, development goals. A case in point is the green revolution. Nobody will deny that the green revolution contributed substantially to the increase in grain production and therefore achieved the goal of greater supplies of staple food. But nor will anyone deny that this was often realized at the expense of the wider development goals of, for instance, a redistribution of income and the achievement of social equality.

At the World Conference on Agrarian Reform and Rural Development (1979), this was a much discussed problem, particularly in relation to the inequality of land distribution among owners and users of the land.

The occurrence of project externalities can often be traced back to the earlier-mentioned inadequate knowledge of the local situation, especially of those factors that lie beyond the control of the farmer. A better knowledge of these factors can also lead to a better-founded opinion on the possibility or not of attaining certain national or rural development goals.

This brings us to the next issue, that of development goals. Each development plan is based on certain development goals, and in a world where social values are rapidly changing, there is also a change in development goals. The Fournex report (UNITED NATIONS 1971) suggests that a redefinition of development goals must include greater stress on income distribution and employment, more attention to social services and welfare-oriented public goods, and greater provision for political participation.

The report also stresses the need for a quantification of social goals in development plans so that actual progress can be measured against these goals. One of the ways to quantify the social goals would be to establish the concept of minimum, or threshold, environmental standards (health, food, housing, etc.). Here, one comes very close to the earlier-mentioned concept of basic needs.

That development goals can sometimes be highly conflicting is clear from the continuing fight over the price policy for agricultural products, particularly the main food crops. On one side are the producers who must receive a price that guarantees them a reasonable income (one of the producers' minimum environmental standards) while on the other side are the nonproducing consumers who must be able to buy sufficient food at reasonable prices (one of the consumers' minimum environmental standards).

Here is not the place to go further into these issues. Suffice it to say that the development process is a highly complex one, calling for an approach that can integrate numerous technical, social, and economic factors, all of which have to be considered simultaneously.

With all the risk inherent to any oversimplification, one could say that the current development effort is characterized on the one hand by endeavours to broaden development goals as advocated in the Fournex report, and on the other by the compelling need to raise food production to meet the increasing demand.

The problem dominating all else for the immediate future would seem to be the striking of a balance between these two often contradictory goals – a balance that will have to be found not only within the framework of the limited means available (and means are always limited) but to find it in time to safeguard the imperilled world food situation.

Conclusions

In the decades that lie ahead of us, land and water development will have a vital role to play in striving to increase the world's food production – an increase that must primarily take place where food shortages are to be expected, i.e. in the developing countries. Not only must food production be raised, there must also be significant improvements made in the incomes of large groups of the rural population of those countries.

Efforts should first concentrate on raising productivity per unit of land. The low yields obtained on arable land in the developing countries as against the high potential of those lands make it possible, technically speaking, to raise production many times over, and, what is more, to do so at an investment level far below that of developing new land.

It is alarming to observe that the development of new land scarcely keeps pace with the loss of land due to degradation and urbanization. All possible steps must be taken to prevent further degradation of land. The rehabilitation of existing irrigation schemes and improvements in the drainage of irrigated and non-irrigated lands are in line with this viewpoint.

Land and water development to raise food production and improve the income of rural people demands tremendous world-wide investments, not only for primary investments at project level but also for the vast scala of secondary investments that must be made if the projects are to achieve their ultimate objectives. A substantial increase is required in both the external aid volume and the internal contribution by the developing countries themselves, not merely to keep pace with the demand for food but to raise living standards in general.

Two matters will be decisive for the success of these undertakings. These are:

- The political will on the part of both the richer and the poorer countries to unite in a concerted effort to realize the ambitious but vitally necessary programs that must bridge the prosperity gap between the two halves of the world.
- Within the development effort, a balance must be struck between the sometimes conflicting goals of a broader-based development and the compelling need to raise food production.

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From soil survey interpretation to land evaluation

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History

The increasing and competitive demand for land, both for agricultural production and for other purposes requires that decisions be made on the most beneficial use of limited land resources, whilst at the same time conserving these resources for the future. The function of land evaluation is to bring about an understanding of the relationships between the condition of the land and the uses to which it is put, and to present planners with comparisons and promising alternative options.

Since time immemorial, man has evaluated land for his own, mainly rural, purposes. The men that Moses sent to spy out the land of Canaan (Numbers 13:21) reported having found a land flowing with milk and honey. Apparently they considered this land very suitable for the types of land use they had in mind: camel-grazing on the semi-arid plains and date-growing at the oases. The Bible also reports that it took Moses's land evaluators four months to reach their conclusions and report back to headquarters.

Since then the techniques of land evaluation have evolved substantially; the duration of the process has grown too. The evaluation in biblical times required four months; it took Brazilian land evaluators all of the 1970's to explore and report on the Amazon Basin. (Admittedly, the Amazon Basin is 4 million km^2). The Brazilians had at their disposal aerial photographs at a scale of 1:400,000 – photographs that were totally unaffected by the persistent cloud cover, being taken with side-looking radar from high altitude aircraft. When helicoptered into remote places, sometimes populated by hitherto undiscovered Indian tribes, the land evaluators could make use of LANDSAT satellite imagery, colour and infrared photographs at a scale of 1:130,000, multispectral photographs at a scale of 1:70,000, and black-and-white video tapes at a scale of 1:23,000. To analyse their soil samples, they had atomic adsorption spectrophotometers available at the local laboratory. For climatic analyses, they could resort to data from hundreds of meteorological stations.

Apart from this development in techniques, there has also been a development in the approach to land evaluation.

Soil science was given a great opportunity to develop during the 1930's when the sudden uncontrolled intensification of settlement and agricultural land use threatened the very foundation of human existence: its food production. But with the rapid development of soil science and the unavoidable proliferation of its technical jargon, it was gradually realized that a wall was being raised between the soil scientists and those who needed the results of their work – from planners and engineers to extension workers and subsistence farmers. Soil survey reports were put aside because their potential users could not interpret the too technical information. Soil scientists were challenged to broaden their vision or, as Professor Cline of Cornell University put it: 'They should attempt to look at soils the way the farmer does'. Renowned soil scientists such as EDELMAN (1963) and KELLOGG (1961) advocated in clear writing the need for a closer association with the users of their information. Their vision paved the way for a relatively small number of soil scientists to dedicate their efforts to the full and effective application of the knowledge available about soils.

Before World War II, in response to the suddenly realized need for a convenient interpretation of land characteristics in planning and applying soil conservation measures on farms, the USDA-SCS Land Capability System was developed. The postwar years saw the development of other systematic applications of soil information, which were concerned with yield prediction and soil and water management. The Land Classification System for Irrigated Agriculture, as developed by the U.S. Bureau of Reclamation, is an example of this. The systematic synthesis and presentation of information on the characteristics and behaviour of soil, as classified and outlined on maps, became known as 'soil survey interpretation' (BARTELLI et al. 1966).

Recent developments

Soil survey interpretations are predictions of performance, not recommendations for the use of soils. Agricultural land use requires not only that crops and/or livestock grow, but also that the land is conditioned for optimal productivity: that the seedbed is prepared, the crop is sown, protected against hazards, pests, diseases, weeds, that it is harvested, transported and processed. Depending on the kind of land use these agricultural practices make specific demands on the manageability of the land. In the industrialized countries a more or less uniform, high level of management has prevailed, which has encouraged a nation-wide standardized land evaluation system, either for general land use purposes or specific crops. But in developing countries, very different levels of management exist side by side. In such countries one must be very careful when introducing these alien systems!

Here, the land use assumptions underlying land capability grouping must be more differentiated. One of the aims of today's land evaluation is to provide land use planners with information based on a methodology that uses the same concepts and procedures for any kind of land use so that comparisons and cross references are facilitated. Such a methodology is best served by a systematic approach to the kinds of land use considered, and by explicit mention of the assumptions that have led to their selection.

Aware of the need for precisely defined kinds of land use in systematic land evaluation, FAO undertook the task of developing a world-wide standardized methodology. Two multidisciplinary commissions, one in The Netherlands and one within FAO, prepared a joint paper that was discussed at an FAO Expert Consultation in Wageningen (BRINKMAN and SMYTH, eds. 1973). After another meeting in Rome the FAO Framework for Land Evaluation was published (FAO 1976; ILRI 1977). This Framework tries to incorporate the advantages of existing systems and, by a careful definition of land utilization types and land assessment factors, to avoid some of the pitfalls that inevitably occur when a system that was developed in one country is applied in another country with different land use conditions.

Since the USDA Land Capability System and the USBR Land Classification System for Irrigated Agriculture are probably the best known approaches to land evaluation, I shall discuss them first. Both systems have been modified for use in different countries; in particular the modified systems of soil survey interpretation developed during the 1960's in Brazil and Iran served as major references for the new FAO Framework. This Framework is not in itself an evaluation system but rather a set of concepts, principles and procedures on the basis of which local, regional or national evaluation systems can be constructed. The study of present and potential land use is important when applying the Framework which represents the climax of this quarter century of international methodological reassessment.

USDA Land Capability System

At first, land capability mapping and soil survey tended to be undertaken as separate exercises serving different purposes. But with the advance of soil survey techniques, today's land capability maps are a product of systematic soil survey interpretation.

The earliest and best known system of land capability mapping, dating back to the early 1930's, is that of the Soil Conservation Service of the U.S. Department of Agriculture KLINGEBIEL and MONTGOMERY 1961). This System is based on permanent physical land characteristics that limit land use or impose risks of erosion or other damage that can easily be identified. Important characteristics for interpretation are slope, soil texture, soil depth, permeability, water holding capacity and type of clay. The System groups soil mapping units in eight capability classes on the basis of their capability to produce common cultivated crops and pasture plants over a long period of time. The risk of soil damage or limitations in use become progressively greater from Class I to Class VIII. The most general step of the Capability System is the separation of land suited for cultivation (Classes I–IV) from land not suited for cultivation (Classes V–VIII). Soils having the greatest alternative uses (cultivated crops, pasture, range, woodland, wildlife) are assigned to Class I; soils with the least number of alternative uses (only wildlife, recreation, or watershed protection) are assigned to Class VIII. The Capability System is designed (1) to help farmers and others use and interpret the soil maps and (2) to enable broad generalizations to be made on the basis of soil potentialities, permanent limitations in use, and management problems.

Nowadays land use planning sometimes needs to protect prime agricultural land against competing non-agricultural uses. The Land Capability System provides essential information for this type of planning. For example, in British Columbia, Canada, where arable land represents less than

Table 1.
Slope limits and soil losses within capability classes on three groups of uneroded soils (KLINGEBIEL 1958).

Capability Class	Soil group A[1]		Soil group B[2]		Soil group[3]	
	Slope %	Soil loss[4] tons/acre	Slope %	Soil loss tons/acre	Slope %	Soil loss tons/acre
I	0– 2	0– 5	0– 1	0– 4	–	–
II	2– 7	5– 23	1– 5	4– 15	0– 1	<0.2
III	7–12	23– 53	5– 9	15– 38	1– 5	2–15
IV	12–18	53– 98	9–14	38– 74	5– 9	15–38
VI	18–30	98–189	14–24	74–142	9–14	38–74
VII	30+	189+	24+	142+	14+	74+

[1] Soil having favourable characteristics and qualities throughout 4-feet depth for growth of common agricultural plants. Maximum tolerated soil loss: 5 tons/acre per year.

[2] Soils having moderately favourable characteristics and qualities for growth of common agricultural plants. Maximum tolerated soil loss: 3–4 tons/acre per year.

[3] Soils having unfavourable characteristics at shallow to moderate depths for growth of common agricultural plants. Maximum tolerated soil loss: < 2 tons/acre per year.

[4] Estimated soil loss based on continuous up-and-down cultivation-200 feet slope length.

10% of the total land area, land in the Frazer Valley corresponding to Classes I, II, and III may not be taken out of production to provide space for urban or industrial development.

It must be emphasized that the prime concern of the classification is the risk of erosion, and not productivity. This is why in the classification grazing is given preference over agriculture with increasing hazards of land degradation, while woodland is given preference over grazing. The capability system is not a productivity rating for specific crops; this is nicely illustrated in Northern Portugal, where the best land in the country for producing the world famous port wine is classified as Class VI and VII land.

A major disadvantage of the system is that capability classes are related to soil losses (Table 1) on the assumption of a moderately high level of management (i.e. one that is within the ability of the majority of the farmers in the U.S.A.) whereas in the developing countries very different levels and systems of management occur.

More specific studies of soil erosion will relate expected soil losses not only to the soil but also to the type of crop and the type of soil management. Of all the factors influencing erodibility the crop and management factors are more difficult to assess than the actual physical features of the soil. The differences in erosion caused by different kinds of land use and management practices may be much greater than the differences in erosion from different soils given the same management. When referring to soil loss from two identical experimental plots, HUDSON (1971) reported losses 15 times greater from the plot with a badly managed crop of maize than from the plot with a good maize crop.

The effects of soil and crop management on soil loss from a highly weathered red tropical soil are also relevant here (Table 2).

It may be concluded that general purpose land evaluations such as the USDA Land Capability Classification are useful for broad planning purposes at regional and national levels, provided that their underlying assumptions about management level and land use practices reflect the true situation in the area. For more detailed land use planning decisions, such groupings are of little significance and need to be complemented by separate land evaluations for precisely defined land use purposes.

USBR Land Classification for Irrigated Agriculture

The Land Classification System of the Bureau of Reclamation of the U.S. Department of the In-

Table 2.
Effect of soil and crop management on soil loss (LAL 1976).

Slope %	First season					Second season				
	Bare-fallow	Maize-maize (mulch)	Maize-maize	Maize-cowpeas (no till.)	Cowpeas-maize	Bare-fallow	Maize-maize (mulch)	Maize-maize	Maize-cowpeas (no till.)	Cowpeas maize
1	1.00[1]	0.00	0.20	0.00	0.06	1.00	0.00	0.11	0.00	0.19
5	1.00	0.00	0.10	0.00	0.06	1.00	0.00	0.04	0.00	0.08
10	1.00	0.00	0.08	0.00	0.04	1.00	0.00	0.04	0.00	0.06
15	1.00	0.00	0.14	0.00	0.04	1.00	0.01	0.16	0.03	0.39

[1] cumulative soil-loss factors

terior (USBR 1953) is an interesting example of multidisciplinary land evaluation. It is used for formulating and planning irrigation projects. The system enables the prediction of crop production inputs and yield outputs as a function of physical factors (soil, topography, drainage, climate, water quality) *and* socio-economic factors (technological levels, economic conditions, social organization, resourcefulness of the people, and the development goals).

The planners of irrigation projects are well served by this land classification system because it integrates all these plan-determining elements. Whereas the USDA Land Capability System is based in the first place on a physical principle, 'No soil erosion should occur', this system is based on an economic principle for distinguishing between different (four or six) land classes. Land class is defined as a category of lands with similar physical and economic attributes that affect the suitability of land for irrigation; it is an expression of the relative level of payment capacity. The amount of money remaining for the farm operator after all costs, except water charges, have been met and after an allowance has been made for family living, is identified as the payment capacity. The economic and physical factors are correlated through the relationship between soil, topographic, and drainage factors and productive capacity, production cost, and land development costs for a given project setting. Class 1 has the highest level of irrigation suitability, hence the highest payment capacity. Class 2 has intermediate suitability and payment capacity. Class 3 has the lowest suitability and payment capacity. Class 4 designates special use classes such as 4F fruit, or it is used to designate land with excessive deficiencies but which has nevertheless been shown to be irrigable by special engineering and economic studies. Class 5 is used as a temporary designation for lands requiring special studies before a final land class designation can be made, and Class 6 is land not suitable for irrigation development.

To separate the different land classes in a given project area specific limits of soil properties and other physical parameters are set up. The selected limits underlying such 'land classification specifications' are site-specific, depending on climate and economic setting, and must be prepared anew for each project area. An example is given in Table 3.

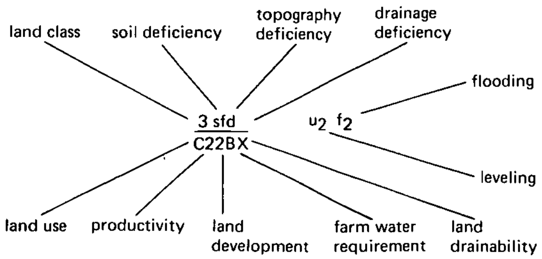


Figure 1.

Example of the mapping symbols used in the Irrigation Suitability Classification (USBR 1953).

Results of the land classification are used for: (1) selection of irrigable lands, (2) determination of water requirements, (3) selection of land use and size of farm, (4) selection of the land development methods, (5) determination of payment capacity, (6) determination of irrigation benefits, (7) development of layouts for irrigation and drainage systems. At present the land classes in the USBR System are defined for 'irrigated farming', without specifying the type of crops, or the type of farming. Sometimes, separate land classes are created for special crops (e.g. paddy) with unusual land requirements. This acknowledged need to be more explicit about the kind of crops to be grown under irrigation indicates that different types of land use (crops, farming systems) can affect the economic and financial feasibility of the same parcel of land.

Originally the USBR methodology of land classification proceeded directly to the survey and mapping of the land classes. All pertinent diagnostic factors of the environment were studied and interpreted simultaneously. This approach can save time and money when the nature of the planned development, including the choice of crops and management practices, is clearly de-

Table 3.
Land classification specifications for irrigation (FAO 1979).

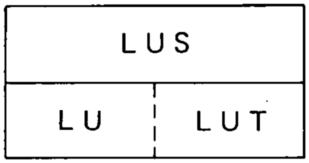
				Climate Zones D and E
	Class 1	Class 2	Class 3	Class 4
SOILS				
Texture (Surface 30 cm)	FSL–CL	LFS–C	Peat & Muck LS–C	LH–C
Moisture Retention (AWHC–120 cm)	> 12.5	10–12.5	7.5–10	7.5–10
Effective Depth (cm)	> 100	75–100	50–75	30–50
Salinity ($EC_e \times 10^3$ at equilibrium)	<4	4–8	8–12	12–16
Surface sodic conditions (Slick spots)				
Per cent of area affected (may be higher with favourable soil minerals)	0–10%	10–25%	25–40%	40–50%
Sodicity (exch. Na meq/100 g soil with irrigation equilibrium) (may be higher with favourable soil minerals)	<1	1–2	2–3	3–4
Permeability of least permeable layer in soil (in place measurement) cm/hr	0.5–5	0.157–15.75	0.157–15.75	0.157–15.75
Permissible cobble %	10	10–25	25–50	same as
Permissible gravel %	15	15–20	50–70	Class 3
Rockiness (small outcrops)	None	0–2% of surface covered	2–10% of surface	10–20% of surface
Soil Erosion				
TOPOGRAPHY (or land development item)				
Stone for removal (m³/ha)	<20	20–45	45–95	95–130
Slope (per cent)	0–2	2–5	5–15	15–20
Surface levelling	Light	Medium	Medium heavy	Medium heavy
Tree removal (amount of cover)	Light	Medium	Medium heavy	Medium heavy
DRAINAGE – Soil Wetness				
Air Drainage		Not applicable to this climate zone		
Depth to Drainage Barrier cm	250	200	175	120
Surface Drain	No problem	Minor problem	Restricted	Restricted

fined and when sufficient is known about the effect of the selected diagnostic factors on irrigated land use. But the increasing need to assess the possibilities of irrigation for a variety of alternative uses, management systems and projects made it desirable to base irrigation studies on systematic soil surveys that could provide the information needed to predict the performance of all relevant land use alternatives (FAO 1979). Especially in climatic zones with pronounced dry and wet seasons, such as the Mediterranean and Monsoon climates, land evaluation must assess the prospects of irrigated agriculture, rain-fed agriculture and the combination of the two.

FAO Framework for Land Evaluation

General

In this Framework (FAO 1976) an attempt is made to treat the process of land evaluation systematically against the background of a land use system (LUS), which has been subdivided into a physical land constituent mostly described by land evaluators in terms of land (mapping) units (LU), and a land utilization type (LUT):



In this way it should become possible to predict the performance of present and alternative land use systems representing different land units/ land utilization type combinations, taking full account of the differences and similarities between the land units identified during the land resources studies.

The Framework describes land evaluation as a process of comparing or 'matching' the land with the use. This is an iterative procedure: knowledge of the land leads to conclusions about which uses may be expected to suit the land in question, while at the same time, in view of physical land limitations, the land uses may be modified or adapted to the land limitations. The matching exercise includes consideration of physical inputs for improving and conserving the land.

From land units to land qualities

Land resources are usually described and presented on maps in terms of land mapping units, which may be more or less heterogeneous. This degree of heterogeneity will also affect the reliability of the land evaluation. Land resources mapping involves an enormous amount of data about soil, climate, hydrology, vegetation etc. But because the data are collected according to discipline, important relations and interactions between different land attributes are often overlooked, particularly those between soil and climate. In many existing systems of land evaluation, single or minor compound land characteristics, such as texture or drainage, are used as a basis for diagnosis and for establishing class-determining specifications (GIBBONS and HAANS 1976). If land characteristics are employed directly in evaluation, problems arise from the interaction between characteristics. For example, the hazard of soil erosion is determined not by slope angle alone but by the interaction between slope angle, slope length, permeability, soil structure, rainfall intensity and other characteristics.

In the FAO Framework, combinations of land characteristics relevant to specified uses are used as assessment factors reflecting limitations to land suitability and are called land qualities (LQ).

Table 4
Land characteristics and land qualities

Land characteristics	Land qualities		
	Risk of water-logging	Work-ability	Drain-ability
Soil texture		x	
Soil permeability			x
Watertable	x	x	x
Infiltration rate	x		x
Topographical level			x
Micro-relief	x	x	x
Precipitation/ Evaporation		x	

Table 5.
Definition of the land quality 'Workability' (BEEK et al. 1980).

Degrees of workability Wk	Potential evapotranspiration (Thornthwaite) during critical months						
	Oct. 64 mm	Nov. 35 mm	Dec. 21 mm	Jan. 22 mm	Feb. 25 mm	Mar. 38 mm	Apr. 52 mm
Number of rainless days after soil saturation							
1	6	9	13	13	13	9	6
2	7	10–11	14–17	14–17	14–17	10–11	7
3	8	12–15	18–23	18–23	18–23	12–15	8
4	9–11	16–18	24–27	24–27	24–27	16–18	9–11
5	12+ days	19+ days	28+ days	28+ days	28+ days	19+ days	12+ days

Table 6.
Measurable properties of workability (BEEK et al. 1980)

Texture of suface soil	micro relief	depth of the watertable (winter)			
		> 80 cm	50–80 cm	30–50 cm	<30 cm
Sand	levelled	Wk 1	Wk 1	Wk 1	–
Sandy loam Loamy sand	uneven	Wk 1	Wk 1	Wk 1	Wk 2
Silty loam	levelled	Wk 1	Wk 1	WK 2	WK 3
Loam	uneven	WK 2	Wk 2	Wk 3	Wk 3
Silty clay	levelled	Wk 2	Wk 3	Wk 3	Wk 4
Loam	uneven	Wk 3	Wk 4	Wk 4	Wk 5
Scl/cl	levelled	Wk 3	Wk 4	Wk 4	Wk 5
Clay loam	uneven	Wk 4	Wk 4	Wk 5	Wk 5

Land qualities are described in terms of measurable land characteristics derived from the land mapping units. Within each land quality a number of constituent single, or minor compound land characteristics would have to be distinguished for rating the land qualities they belong to (Table 4).

Land quality ratings must be significant, given the land use requirements. For instance, workability of the soil can be rated in number of days without rain that are required after the soil becomes saturated, to permit field operations with specified equipment (Table 5).

The degrees of workability have been related to measurable component properties (Table 6).

Yield predictions

An important criterion for grouping land for specific land use purposes is the expected yield (output). The level of expected yield is related to land qualities and inputs. Figure 2 gives an example of input-output relationships, indicating that a land quality, original level of available phosphorus, can be improved and what the consequences are for the yield.

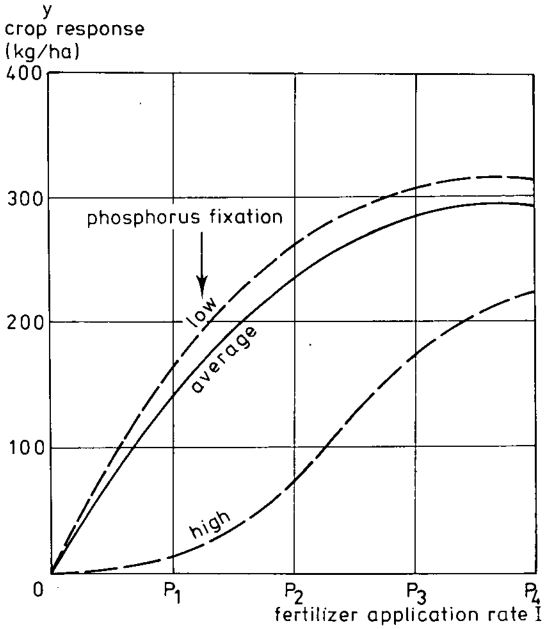


Figure 2.
Hypothetical partitioning of low phosphorus soil test population in two sub-populations with different P-application efficiencies based on different P-fixation levels (BEEK 1978).

However, these relationships are not always available, certainly not for every LUT-LU combination that is considered to be important in the study area. Therefore other approaches for obtaining this vital information are needed, the most obvious one being the transfer of knowledge from analogous situations that are better known, or even the use of simulation models.

There is a tendency to make the analysis of productivity more fundamental by identifying and quantifying the ecological components, e.g. of the water regime (SLABBERS et al. 1979), responsible for limiting the maximum yield that could be expected given the available radiant energy and the genetic build-up of the plant in question. One (very big) step towards such sophistication is the construction of models based on fundamental plant growth and production processes, which include land factors in their equations for calculating theoretical yields (de WIT et al. 1978; FEDDES et al. 1978).

In 1968 NIX presented broad proposals for describing primary biological production as the result of dynamic interactions between genotype and physical environment, taking into account the energy, water, gas and biotic regimes. The CSIRO Symposium on Land Evaluation in Adelaide, Australia, where Nix presented his paper, probably marks the beginning of a more integral approach to the survey and interpretation of land resources. Encouraged by the FAO studies and meetings, 'land evaluation' became a specific area of interest.

One of the results was the FAO Agro-Ecological Zones Project (FAO 1978) which aimed at the assessment of crop productivity on a world wide basis and the preparation of maps indicating zones of similar yield potential for selected crops. This project uses a mathematical model that relates yields of 11 selected important rain-fed annual crops to photosynthesis and respiration losses. Soil factors derived from the FAO/UNESCO Soil Map of the World have also been considered, as qualitative reduction factors. But climate is of course the principal variable. Water availability is computer-calculated in terms of period in days (30-day-intervals) when available water and temperature regime permit crop growth: 'the length of growing period'. A computer programme for matching the crop's climatic and soil requirements with the climate/soil inventory is the basis of the final productivity rating and of the area calculations of the different land classes.

From land utilization types to land use requirements

The characterization of land utilization types may include a variety of factors according to the detail and purpose of the land evaluation study. Depending on the phase of the development planning process and the corresponding intensity of the study, separate alternatives could represent broad differences in agricultural use (irrigated arable farming; rain-fed arable farming; rangeland, etc.), specific aspects of such use (e.g. gravity irrigation; sprinkler irrigation), or even specific crops. Fundamental references for the selection of relevant land utilization types includes:

- overall development situation
- attributes of the land

The overall development situation provides the socio-economic, demographic, legal, institutional and political setting of land evaluation and represents a valuable yardstick for the kind of development to which land evaluation is expected to contribute. In regard to the attributes of the land, a distinction should be made between the socio-economic and the physical attributes of land. Socio-economic attributes such as land tenure, land value, etc. represent an important reference for the selection of pertinent land utilization types; they constitute the context of physical land evaluation, whereas the physical land conditions are the main object in land evaluation.

Figure 3 presents a more detailed diagram of the process of synthesis of land utilization types. From the descriptions of the land utilization types, the land use requirements (LR) that each of them poses on the land should be derived. These land use requirements are the most fundamental aspects of the land utilization types for purposes of land evaluation. The land use requirements of a LUT determine to a great extent

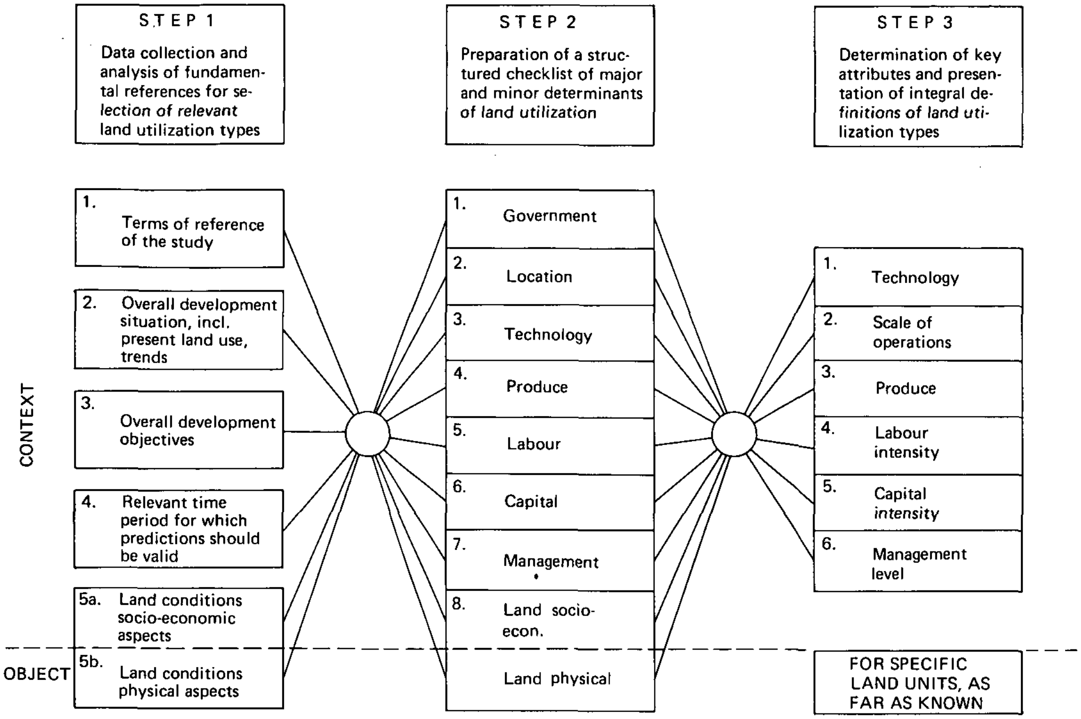


Figure 3.
The process of synthesizing land utilization types (BEEK 1978).

which land resources data need to be studied and in how much detail. In agronomy the term 'requirement' is commonly used when speaking of the specific land conditions required for the proper functioning of a certain crop (or agricultural implement). Examples of requirements include: water requirements, nutrient requirements and seedbed requirements of a certain crop, and the soil moisture and workability requirements needed by certain types of machinery during specific time periods of the year. Because the land use process is continuous and dynamic, in order to facilitate data measurement it will be necessary to disaggregate the land use process into a number of component processes and activities that take place during defined time periods. Each process or activity should be characterized by its own land use requirements. Once the continuous land use process has been disaggregated into a kind of land utilization calendar that specifies in chronological order each pertinent land use process/activity and the corresponding land use requirements, it should become possible to make a problem-oriented analysis of the status of the time-variable land qualities that should meet these land use requirements. Much is already known about the value of LR as far as the land use requirements of specific crops are concerned, e.g. the nutrient and water requirements, resistance to toxic elements such as alkalinity and salinity (Table 7).

Such relationships are useful to determine whether a particular land use requirement, absence of soil salinity, is met by the land quality, actual level of soil salinity, and if not, how much this land quality is limiting the yield (MOORMANN and van BREEMEN 1978).

A very critical aspect of land evaluation is the availability of information about these land use requirements, especially in developing countries. This information is often very difficult to obtain, and may be incomplete or vague. It is not unusual to find that handbooks on the cultivation of tropical crops give the ideal land conditions, which bear little resemblance to the actual land conditions prevailing in the project area where the suitability needs to be evaluated (VINK 1975).

Land use requirements versus land qualities

Matching the land use requirements with the land qualities for a specific combination of land utilization types and land units (LUT-LU combination) indicates how suitable a given tract of land is for a certain use. Diagnosis of suitability entails the prediction of expected outputs, physical inputs, and of changes in the status of the land qualities, e.g. in the sustained productive capacity of the land. Input-output analysis should include in the first place the study of the relation between land qualities and the outputs, and the relation between inputs and outputs. These relations are interrelated and depend on the land utilization type under consideration, because each land utilization type can be different in its requirement for a certain land quality. These

Table 7.
Crop salt tolerance levels for different crops (adapted from AYERS and WESTCOTT 1976).

	Yield potential								Max. ECe
Crop	100%		90%		75%		50%		
	ECe[1]	ECw[2]	ECe	ECw	ECe	ECw	ECe	ECw	
Barley	8.0	5.3	10.0	6.7	13.0	8.7	18.0	12.0	28
Cotton	7.7	5.1	9.6	6.4	13.0	8.4	17.0	12.0	27
Rice (paddy)	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	12
Sorghum	4.0	2.7	5.1	3.4	7.2	4.8	11.0	7.2	18
Wheat	6.0	4.0	7.4	4.9	9.5	6.4	13.0	8.7	20

[1] Electrical conductivity of the saturation extract of the soil in millimhos per cm at 25 °C.

[2] Electrical conductivity of the irrigation water in millimhos per cm at 25 °C.

two relations and the input/land-quality relation together represent the relation structure of the land use system (LUS):

- land-quality/output relations (LQ/Y)
- input/output relations (I/Y)
- input/land-quality relations (I/LQ)

For defining land suitability classes, attention should be given to the selection of land suitability criteria for land evaluation. Examples of land suitability criterion variables could be:

- yield level
- performance reliability
- flexibility for timing of field operations
- flexibility in choice of equipment for field operations
- levels of physical inputs required
- sustained production

The land suitability classes stand for different values of each criterion variable corresponding with the different degrees to which the land use objectives are expected to be met. In the absence of a common denominator for criterion variables of different dimensions, the land suitability classes are mostly verbal descriptions of the degree to which the land use objectives are met.

To reach the desired goal of land evaluation, i.e. the optimal utilization of land, the 'best' combination of LQ, LR, I and Y must be found, based on explicit land suitability criteria. The systematic breakdown of the land use system into measurable land qualities, land requirements, inputs and outputs is the foundation of a systems approach to land evaluation (see Figure 4).

In Figure 4 a distinction is made between descriptive and prescriptive land use systems analysis.

During the descriptive analysis, physical inputs for manipulating constraining land qualities are compared with their effects on these land qualities and on the outputs, e.g. yield projections. This analysis provides the decision maker with information about alternative land use possibilities. During the prescriptive analysis or land suitability classification, for each LU-LUT combination the input/land-quality output combination that places the land unit in the highest possible land suitability class is selected: these combinations are the soil and water management recommendations.

Reconnaissance type land evaluations often have to rely on a limited data base and a rather qualitative descriptive input/output analysis. But the recent investigations conducted by the FAO Agro-Ecological Zones Project and the Centre for World Food Studies in Wageningen are now developing more quantitative methods. This is important for pinpointing high potential areas where detailed investigations are justified, and for regional planning purposes in general.

Detailed land evaluations should always be as quantitative as possible in their descriptive input-output analysis. Such analyses underlie important planning decisions concerning land improvement and the introduction of new farming systems.

The descriptive analysis may satisfy most, if not

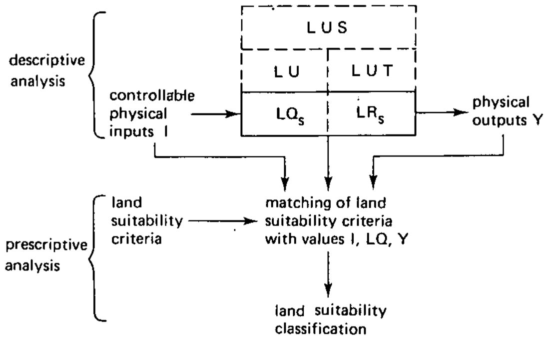


Figure 4.
A diagrammatic representation of systems analysis in land evaluation (adapted from BEEK 1978).

all data needs of the land use planner for establishing optimal crop rotations or farm sizes and in selecting the most economic project alternative. Land evaluation should not assume *a priori* that the 'best' alternative will always be implemented, but should present its conclusions on land suitability as separate classifications for carefully planned alternative options. This gives the planner more flexibility in making his planning decisions, as it provides him with a deeper insight into the development possibilities in the project area.

Expected developments

Whereas the FAO Framework for Land Evaluation represents a milestone in the evolution of a realistic approach to land evaluation, it still relies heavily on data collection, and for practical reasons there is a limit to the number of observations of natural phenomena and experiments that can be made relating to one specific site (VELDKAMP 1979). The ideal of sufficient reliable data from the project site is defeated by time and money. Therefore there is an obvious need for additional techniques to generate information about the expected effect of physical inputs on outputs and on the land itself. Making analogies with other areas has been the most common technique for obtaining such additional data (BENNEMA 1978). But one cannot always rely on the correlation with analogous areas, since many development situations are characterized by a unique combination of socio-economic and physical constraints and very specific development objectives. As the analysis of physical input/output relations also tends to become more and more complex, systems analysis and simulation will need to be increasingly relied upon. Mathematical and analogue models will probably become valuable tools for the study of specific land qualities and land use processes. The models will relate foremost to specific partial land evaluation problems, e.g. of water movement in the soil, soil tillage, the behaviour of plant nutrients and chemical fertilizers and the prediction of potential yield (WIND 1979; FEDDES and van WIJK 1977). The use of mathematical models solely for simulating all input/output relations influencing the performance of a land use system will probably remain too complex to satisfy practical land evaluation entirely in the immediate future. Since the task of modelling and simulation is likely to be beyond the scope of routine land evaluation, specialized institutes should be asked to carry out the more detailed problem analyses. For a better characterization of the environmental regimes (i.e. land qualities), modifications may be required in the data-collecting stage of land evaluation, the methods and density of sampling, the techniques of making land resources maps and the classification of land attributes. More attention should be paid to the study of 'land' and 'landscape', rather than to the study of components only, such as soil, climate, vegetation, hydrology (ZONNEVELD 1979).

Land evaluation must compromise between scientific ideals and the limitations set by the availability and reliability of data and the means available for handling these data. Furthermore, land evaluation is concerned with prediction, which signifies that its results cannot exceed certain limits of probability because of the variation in weather conditions and human behaviour. Recent investigations in the field of ecosystems and theoretical plant production are increasing our understanding of fundamental biological processes. Such contributions are of great conceptual significance for land evaluation. In addition, soil scientists and agricultural engineers are increasing our understanding of mechanisms underlying the various soil and water management and engineering practices. Meanwhile, land evaluation is likely to continue making its predictions of land use performance by interpreting site-specific data and relying on the transfer of knowledge by roving specialists with a 'good eye' for the land. This human capacity, which must have already been Moses's concern when he had to select his men for spying out the land of Canaan, is nowadays often found amongst soil surveyors and physical geographers, who have the opportunity to develop singular skills for observing and correlating multiple natural phenomena, so important to land evaluation. How to translate the rather intuitive knowledge of these modern-day prophets into workable manuals is probably the greatest challenge facing land evaluators in the immediate future.

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Problem soils: their reclamation and management

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INTRODUCTION

Most agriculture in the developed countries is nowadays being practised on the soils most suitable for that purpose. Because of this trend and because of the steadily rising productivity of these soils, EEC countries and the U.S.A. have even been able to reduce their cultivated area.
The situation in the developing countries is in marked contrast. There, although the productivity of the better soils could still be improved substantially, and although enormous land reserves exist in some of the countries (for example, Latin America), much of the agriculture in developing countries is nevertheless practised on soils that are unsuitable or only marginally suitable. In large areas of Asia and Africa, overall productivity is declining because of soil exhaustion and because areas of problem soils are being taken into cultivation. In many developing countries, good soils are scarce, and not even far-reaching political and socio-economic changes can solve the problems of the many low-income farmers who are totally dependent on a small plot of land of limited productivity.
There is scope for some alleviation through investment projects for irrigation, drainage, flood control, and settlement. But the success of such projects depends greatly on the soil. There have been too many unforeseen repercussions on soil quality and land use performance—too many examples of soil compaction, salinization, sodification, erosion, acidification, subsidence, and inundation—all of which happened because the projects did not fully take into account the problems posed by the soils. They failed to develop locally adapted farming systems or appropriate management techniques for problem soils.
Many kinds of problem soils exist in the world, each of them hampering agriculture in one way or another (DUDAL 1976). Red tropical soils, sandy soils, and shallow soils pose problems of soil fertility and soil conservation. Other soils pose problems of water management. This article looks at some of the latter soils: vertisols, peat soils, acid sulphate soils, planosols, fine-textured alluvial soils, saline and sodic soils. Their potential is often discussed in development projects when they occur in conjunction with soils that are easier to manage. Sometimes, when they predominate in hitherto unexploited areas, they attract investments that might be better channelled into more promising sectors of the agricultural economy.
By drawing attention to these soils, by emphasizing the ways their properties affect their reclamation and improvement, by discussing some of the lessons learned during the last decades, and by mentioning local solutions to the proper use of these soils, we hope to contribute to a better understanding of the problems encountered and the risks involved when such soils are used for agriculture.

VERTISOLS

W. A. Blokhuis

Properties

Vertisols are a specific group of poorly-drained fine-textured soils that, like most poorly drained clay soils, are generally found on sedimentary plains, both on level land and in depressions. Smaller areas of vertisols are found on hillslopes and piedmont plains. They occur in climates ranging from sub-humid temperate and mediterranean to semi-arid and sub-humid tropical, with marked dry and wet seasons. The distinctly seasonal rainfall ranges from 150 mm to 2000 mm but is generally between 500 and 1000 mm per annum.

The largest expanses of vertisols occur in Africa (105 million hectares), Asia and the Far East (57.8 million hectares), and Australia (48 million hectares); see Table 1 and Figure 1.

Vertisols owe their specific properties to the dominance of swelling clay minerals, mainly montmorillonite. They show a great uniformity in physical characteristics, since these are largely dictated by the high clay content (40–80 per cent) and by the specific clay mineralogy.

In the dry season the soils develop wide and deep cracks. These cracks close when the clays swell after the first rains. The swelling causes tensions leading to internal mass movements in the soil (churning or pedoturbation). This causes a characteristic structure to develop, with wedge-shaped structural aggregates in the surface soil and large, slickensidefaced planar soil blocks lower in the solum.

Under the poor drainage conditions that are common in vertisol regions, leaching of soluble weathering products is severely restricted, pH is above 7, and there is much available calcium and magnesium. These conditions favour the formation of smectite-type clay minerals, notably montmorillonite.

In semi-arid areas, free carbonates and gypsum accumulations are common. Saline and sodic vertisols may develop under irrigation, but they are rare under natural conditions.

Most vertisols have a rather high but unbalanced fertility status. Vertisols can produce crops year after year at a sustained, albeit low level, without being fertilized or manured. This is because the pedoturbation continuously brings subsoil to the surface. Any nutrient deficiency problems can easily be remedied: nitrogen is always too low and often phosphate is too. Some fixation as trical-

Table 1.

Regional distribution of vertisols (based on data from FAO/UNESCO Soil Map of the World; length of growing periods according to FAO Agro-Ecological Zones Project, Rome).

Region	Area (10^6 ha)	Area (million ha) per length of growing period[1]			
		<90 days	90–180 days	180–300 days	> 300 days
Africa	105.0	38.7	42.3	22.8	3.2
Near and Middle East	5.7	1.6	3.1	1.0	–
Asia and Far East	57.8	14.6	38.7	3.9	0.6
Latin America	26.9	2.7	6.7	10.1	7.4
Australia	48.0	–	–	–	–
N. America	10.0	–	–	–	–
Europe	5.4	–	–	–	–
World total	258.8				

[1] The growing period is the period (in days) during a year when precipitation exceeds half the potential evapotranspiration, plus a period required to evapotranspire an assumed 100 mm of water from excess precipitation (or less if not available) stored in the soil profile (FAO 1978).

cium phosphate may occur, but it is far less than in the acid tropical soils (oxisols, ultisols) of wetter regions. Response to potassium is variable. Secondary elements and micronutrients are often deficient. In the last decade it has been shown that careful fertilization can double or triple the yield of crops such as sugar cane and cotton (DUDAL 1965).

Vertisols differ in surface characteristics and these strongly influence their reaction to soil tillage operations. There are two broad groups:

- the *self-mulching vertisols*. These have a fine (granular or crumb) surface soil, 2–30 cm thick, during the dry season. This fine tilth is produced by dessication and soil shrinkage. When such soils are ploughed, the clods, after being subjected to repeated wetting and drying, disintegrate. When this mulch is well developed, seedbed preparation is hardly necessary,
- the *crusty vertisols*. These have a thin, hard crust in the dry season. When ploughed, crusty vertisols produce large, hard clods that may persist for 2 to 3 years before they have crumbled enough to permit the preparation of a good seedbed (DUDAL 1965). Such soils require mechanical tillage if they are to be cultivated.

The self-mulching versus crusting characteristic is related to the tensile stress of the soil. One of the factors that influence this stress is soil texture. In the Sudan, vertisols were found to be self-mulching when they had clay contents of 60–80 per cent, whereas crusty vertisols in the same region were more sandy and less clayey (e.g. 50 per cent clay; 35 per cent sand). Soils are also strongly self-mulching when they contain appreciable amounts of fine, sand-sized calcareous concretions: these apparently disturb the continuity of the clayey soil material. JEWITT et al. (1979) found that the surface mulch of vertisols in the Sudan is not well-developed where the rainfall exceeds 500 mm. Other observations have shown that under higher rainfall vertisols do not generally contain calcareous concretions. Very high amounts of sodium favour the formation of a hard surface crust.

Problems

When dry, vertisols have a very hard consistence, whereas when wet they are very plastic and very sticky. The optimum soil moisture range for tillage (moist soil with a friable consistence) is narrow and vertisols are rarely in this state for long. With the use of heavy machinery, however, tillage operations can also be performed in the dry season. Mechanical tillage in the wet season causes serious soil compaction. Really wet land is impassable.

Dry vertisols with a surface mulch or fine tilth have a high infiltration rate. When the soil is wet, however, the clays swell, closing the cracks and surface macropores. The soil thus becomes almost impermeable.

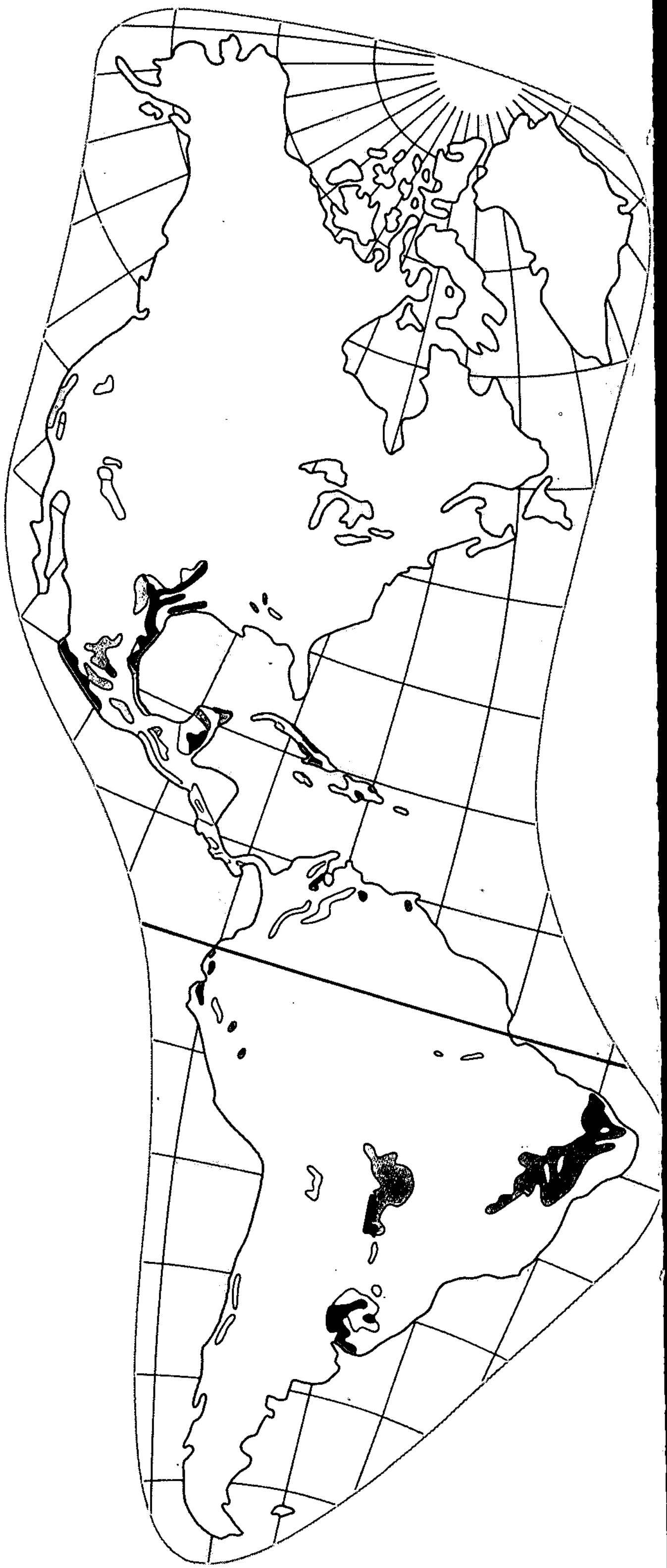
Vertisols have a very low hydraulic conductivity: there is practically no water movement once the soil has reached its field capacity. As moisture penetration is limited, the volume of soil in which water is stored is small. Flooding can be a major problem in areas with higher rainfall because stagnant water can hamper tillage operations. The surface water can be drained by open drains, or crops can be grown on ridges and the intervening furrows used to direct the excess water to a main collector drain. Mole drainage is virtually impossible.

As vertisols have a low structural stability they are very susceptible to water erosion. Slopes above 5 per cent should therefore not be used for arable cropping, and on gentler slopes contour-cultivation with a groundcover crop is advisable, or the land can be used for pasturage. When terracing, sufficient surface drainage must be provided to avoid slumping.

Successful forest plantations have been reported from some countries, but in general tree crops do not do well on vertisols: they lean and their roots can be broken when large cracks develop in the soil. In addition, the low subsoil porosity in the wet season discourages root development.

The adverse physical properties of vertisols have been a major obstacle to agricultural land-use in low-technology societies: these soils are 'heavy' in the true sense of the word and are very difficult

Figure 1.
Worldwide distribution of vertisols (adapted from FAO/UNESCO Soil Map of the World 1971–1979).

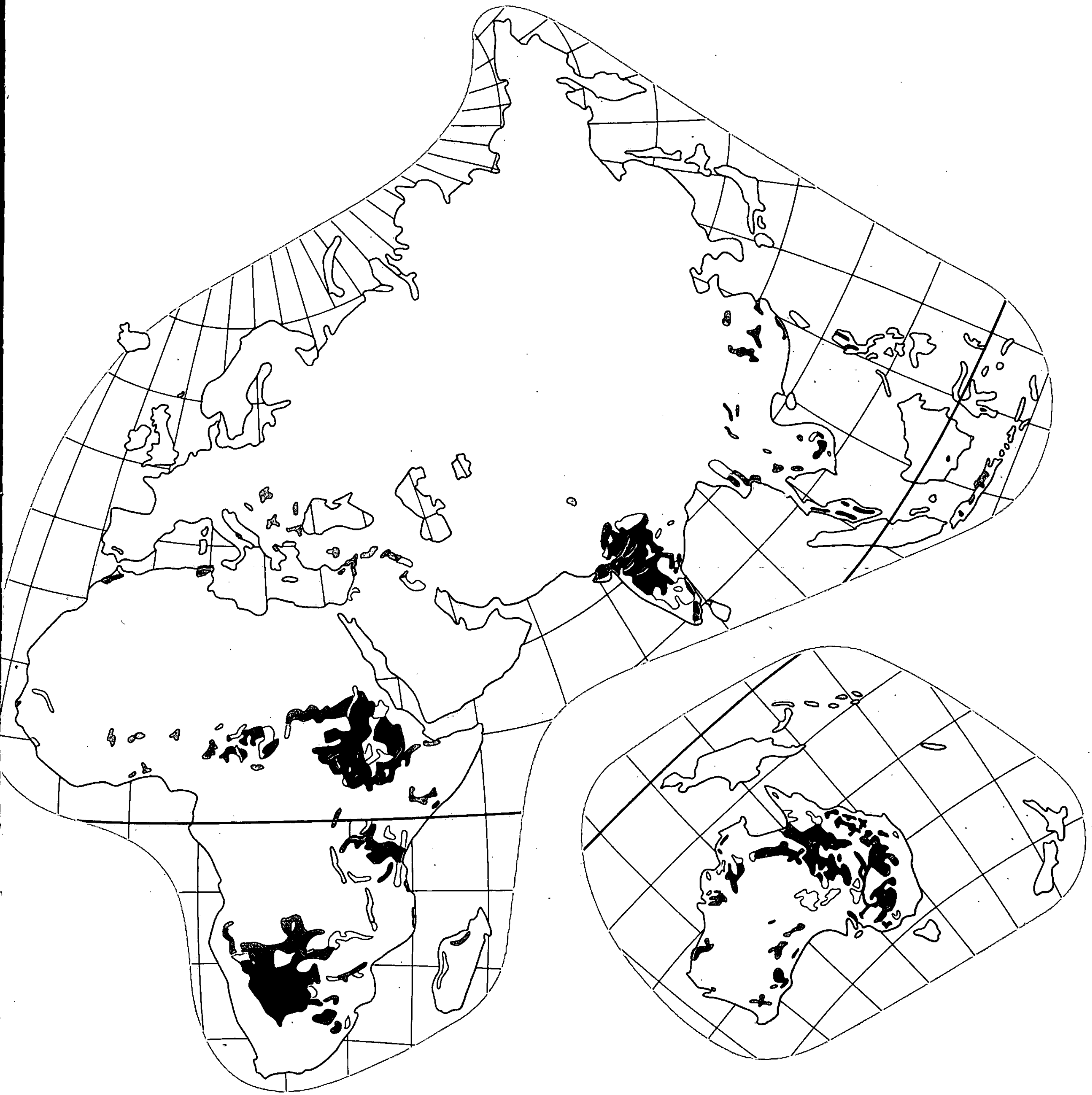


■ dominant
covering 30–100% of the soil association

□ not dominant (associated)
covering 20–30% of the soil association

▨ not dominant (inclusions)
covering 5–10% of the association

source: FAO/UNESCO soil map of the world



to work with hand-powered implements.

Saline and sodic vertisols may develop under irrigation when the irrigation water is of poor quality. Once such a situation exists, soil improvement becomes very difficult. In some cases vertisols with measured exchangeable sodium percentages (ESP) of 40 and above – well above the 15 per cent that has been used to define sodic soils – have produced good yields. Sodic soils with such exceptionally high ESP's have been found to contain the zeolite mineral analcime, and part of the sodium may occur trapped within this mineral. In standard laboratory procedures, part of this 'zeolite sodium' is extracted, in addition to the 'plant-available sodium' that occurs adsorbed on the clay surfaces.

Present land use

In many tropical countries vertisols have been left uncultivated because of their management problems, even though nearby kaolinitic clays and coarse-textured soils with a much lower nutrient status have been cropped. Large areas of vertisols are still uncultivated or are used for grazing. A relatively small proportion is used for crop production, mainly in rain-fed agriculture, whereas a minor part is cropped under irrigation.

Possibilities

The Gezira Scheme in the Sudan (approximately 700,000 hectares) is a successful gravity irrigation project on vertisols. Irrigated agriculture has greatly benefited from the excellent quality of the irrigation water from the Blue Nile. Cotton was and still is the main crop, but since about 1960 diversification from cotton has been achieved. Cropping intensity has also been increased, largely by reducing the fallow period. Both tendencies have necessitated a gradual change from hand and animal labour towards mechanization. Machinery is now in use for tillage operations in combination with weed control, for crop protection, and for the cleaning and maintenance of irrigation canals.

Extensive mechanized crop production schemes with rain-fed agriculture occur in areas with precipitation over 500 mm. Mechanization has proved successful in the reclamation of these areas if they have uniform soil conditions over extensive level plains and a scanty vegetation.

Sudan's large expanses of vertisols are a great potential asset for agriculture. There is considerable scope for an extension of the mechanized schemes and for intensification of non-irrigated farming. As well, enough water is available to allow a considerable increase in the area under irrigation.

Vertisol cultivation in India, unlike that in the Sudan, is generally rain-fed agriculture on smallholdings. Nearly 20 million hectares of vertisols are fallowed during the rains and cultivated after the rains have receded; the main crops are sorghum and maize. It is also possible for vertisols to produce two crops – one in the rainy season and one afterwards – provided that tillage operations and planting dates are carefully planned (and this is difficult because of the unpredictability of the onset of the monsoon) and that crop varieties with an advantageous maturation period are selected (VIRMANI et al. 1977).

PEAT SOILS

P. M. Driessen

Properties

True peat soils have an organic matter content of 65 per cent or more and a minimum depth of 50 cm; they form where the production of organic debris exceeds its decay because of low soil temperatures, waterlogging, severe acidity or oligotrophy, or a combination of these. Peat soils occupy some 240 million hectares worldwide, mainly in boreal and temperate regions. An estimated 32 million hectares occur in the tropics, of which more than 20 million are in the coastal lowlands of southeast Asia (Table 2, Figure 2).

The chemical and physical characteristics of peat soils differ greatly from those of mineral soils. Consequently, the reclamation and use of peat for agriculture requires an entirely different approach. If properly reclaimed and managed, most peat soils can be highly productive on a sustained basis.

The wide variation in the physical characteristics of peat is matched by an equally wide variation in chemical properties. The composition of the organic fraction is largely determined by the floristic composition; lignin, cellulose, hemicellulose, proteins, sugars, and 'humus substances' (including the agressive humic and fulvic acids) are the main components.

Although calcareous peats are not rare, most virgin peats are acid (pH 3.5–5.5) and, compared with mineral soils, contain only low quantities of plant nutrients per unit volume. Often there are very few available micronutrients. Yet, even thick and rain-dependent peats may support a luxuriant climax vegetation. Nutrients are taken up by this vegetation, temporarily stored and subsequently returned to the soil in litter and other plant debris. Removal of the natural vegetation as a reclamation measure interrupts this cycle and is often followed by a rapid decrease in natural soil fertility.

Not all nutrients contained in the peat are readily available for uptake by crops. Only a few per cent of the nitrogen present is available to plants: the rest is tied up in stable organic compounds. Phosphorus is also partly fixed. The availability of potassium is better, but contents are commonly very low.

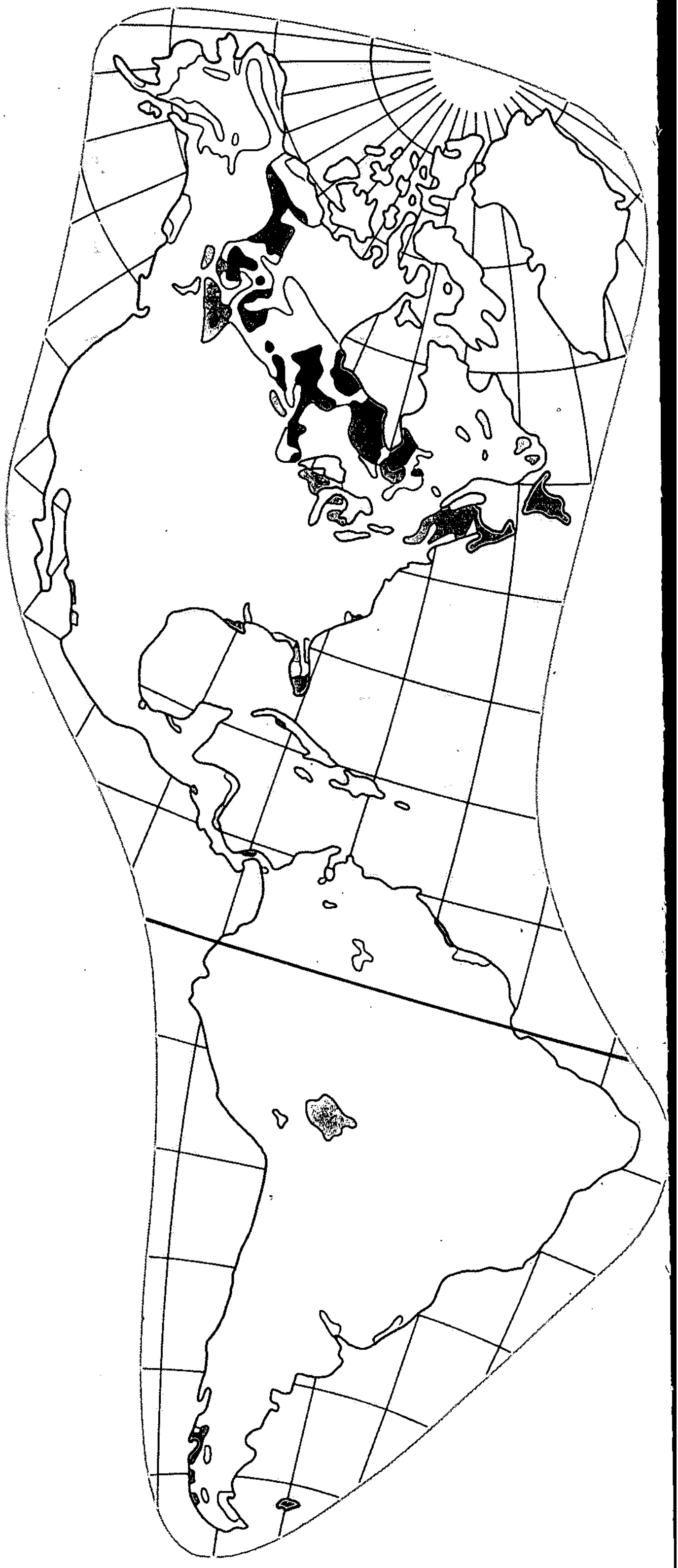
Problems

The major differences between peat and mineral soil material are peat's low bulk density, colloidal nature, and specific thermal properties. Its high porosity creates problems if peats that are almost saturated with water are reclaimed for the cultivation of dryland crops. The necessary drainage removes groundwater buoyancy and is invariably associated with compaction of the loose peat mass and with considerable subsidence of the

Table 2.
Regional distribution of peat soils (based on data from FAO/UNESCO Soil Map of the World; length of growing periods according to FAO Agro-Ecological Zones Project, Rome).

Region	Area (10^6 ha)	Area (million ha) per length of growing period			
		<90 days	90–180 days	180–300 days	> 300 days
Africa	12.2	0.5	3.1	4.9	3.7
Near and Middle East	–	–	–	–	–
Asia and Far East	23.5	0.3	0.2	6.9	16.1
Latin America	7.4	1.1	0.2	3.6	2.5
Australia	4.1	–	–	–	–
N. America	117.8	–	–	–	–
Europe	75.0				
World total	240.0				

Figure 2.
Worldwide distribution of peat soils (adapted from FAO/UNESCO Soil Map of the World 1971–1979).

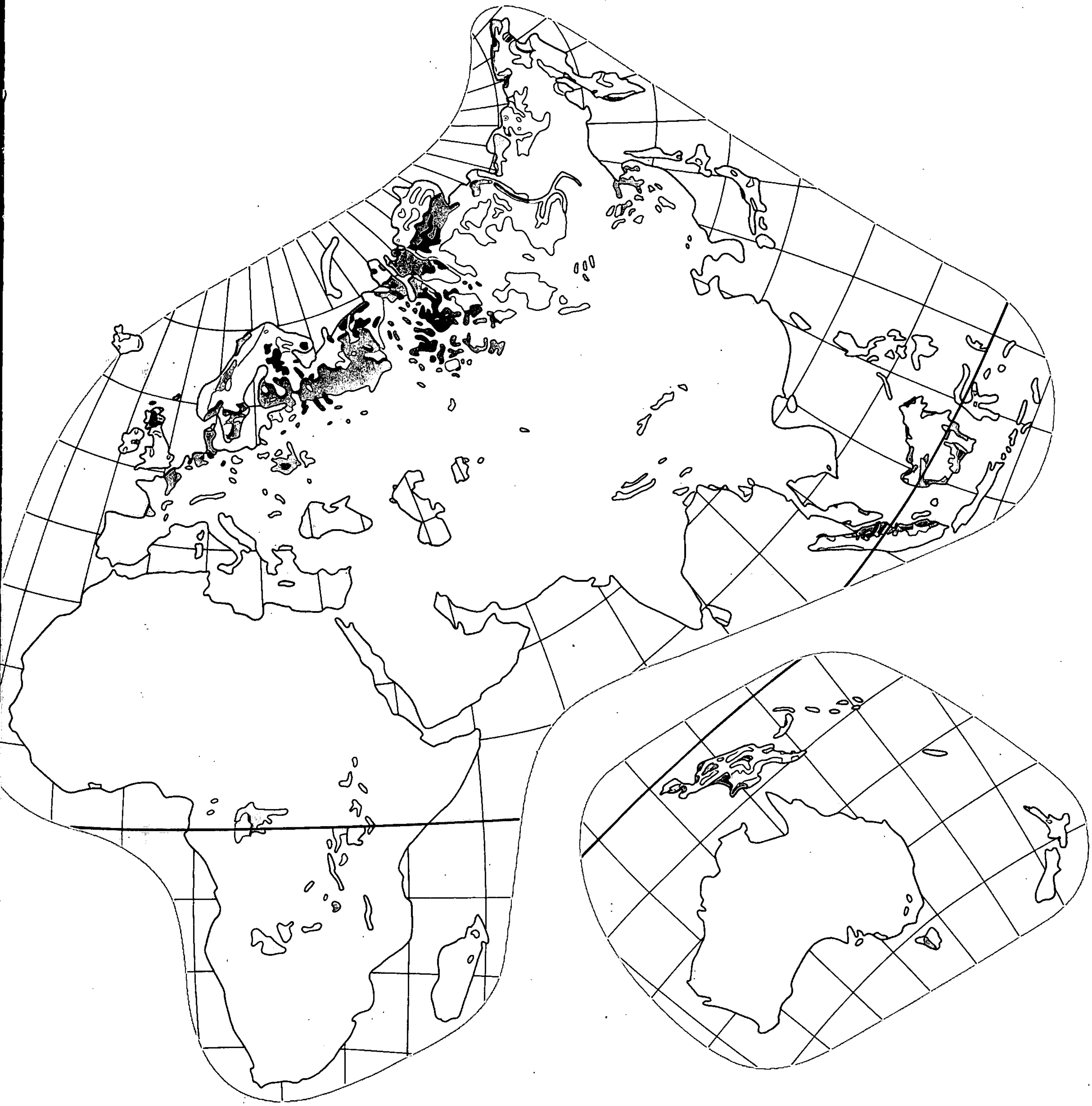


■ dominant
covering 30–100% of the soil association

□ not dominant (associated)
covering 20–30% of the soil association

▨ not dominant (inclusions)
covering 5–10% of the association

source: FAO/UNESCO soil map of the world



land surface. In addition, the high pore volume and the flexibility of fibrous peat material result in a low bearing capacity which hampers the construction of roads, buildings, and water works, and causes top-heavy crops and trees to lean or fall.

Sudden deep drainage may lead to considerable drying and shrinkage of peat. The process is accelerated in bare soils; the low heat conductivity of the organic material allows very high temperatures to build up in the upper few centimetres of peat soils exposed to direct solar radiation. This causes irreversible transformation of colloids and makes the peat crumble to a dry powder with unfavourable physical properties and a high susceptibility to wind erosion.

The obvious way to conserve peats is to keep them under a permanent plant cover and to maintain a shallow watertable. Unfortunately, these measures can seldom be combined because most arable crops need a sufficiently deep root zone for good growth. In addition, wet peat soils are colder than most mineral soils and this retards crop development. Artificial drainage can seldom be avoided. Drain spacings depend on the drainage depth required, the type of peat, its degree of decomposition, density of packing, heterogeneity, and content of wood or mineral admixtures. Drainage systems are likely to need adjustment after some years of operation because the changes induced in water regime affect the hydraulic properties of the peat. It is often contended that reclaimed peats have physical properties that are ideal for agriculture. This is only partly true. Most peat soils have good water-holding and rooting properties and allow easy harvesting of tubers, rhizomes, or peanut pods. However, the perishable nature of the peat requires intelligent soil management and costly measures to combat the degrading effects of shrinkage, settlement, compaction, mineralization, burning, and wind erosion.

The commonly low chemical fertility of peats causes problems when the natural vegetation is abruptly replaced with agricultural crops. This interrupts the cycling of plant nutrients and leads to rapid chemical exhaustion of the peat, particularly where annual crops are grown on oligotrophic material. Only a few years of exploitation may lead to nutrient levels that are too low for the natural vegetation to regenerate. It is mainly this process that accounts for the loss of thousands of hectares of tropical peat swamp forest each year.

Controlled burning of peat lands is often applied as a means to liberate nutrients, particularly where agriculture is practised on a subsistence basis. Burning undoubtedly has a stimulating effect on plant performance but in the long run it destroys the upper (= best) part of the soil profile and seriously damages the structure in the underlying strata. Burning is an inefficient procedure anyway because no crops can be grown at the time of burning and most of the nutrients are lost to the atmosphere or leached out of the rooting zone.

Present land use

The boundary between reclamation and use of peat soils is often somewhat arbitrary; cropping can actually be a reclamation measure. In the first years of cultivation, crop choice is co-determined by factors such as subsidence rate, water regime, and compaction/firmness of the rooting zone. After a few years, land subsidence decreases and becomes a matter of mineralization of the organic material rather than shrinkage or compaction. The soil becomes 'stable' and its increased bearing capacity permits the cultivation of trees and top-heavy crops like papaya and banana.

Peat lands in temperate areas are often used as pastures to avoid the need for deep drainage, but in the tropics a lack of suitable high protein grasses and a score of socio-economic problems hinder livestock farming on peat.

Possibilities

In Europe the reclamation of bogs dates back to ancient times when roads and ditch systems were constructed in peat areas situated above mean sea level. Peat reclamation was already a normal practice in the early Middle Ages and gained new impetus in the 15th century when windmills were introduced to complement gravity drainage.

Large tracts of peat land were reclaimed in western Europe in the 19th and 20th centuries, when improved equipment and legislation made it possible to convert exploited peat bogs into good quality agricultural land. A similar development took place in other peat areas in the temperate zone; millions of hectares were reclaimed for the production of grains and potatoes in the U.S.S.R. and also on the American continent.

The reclamation of tropical peat lands is more recent. Peat bogs in the tropics are commonly opened by individual farmers although some medium-sized centrally controlled projects have also been implemented, particularly in southeast Asia. Examples of successful farming pursuits on tropical peat are the pineapple plantations of Malaysia and some prosperous horticultural areas on peat in Peninsular Malaysia, Sarawak, and Kalimantan. The results obtained by experimental stations suggest that reclaimed peats hold out good prospects for the cultivation of a wide range of crops, including several oil crops, fibre crops, stimulants, and vegetables. The high and recurrent inputs required account for the marginal use that is at present being made of tropical peat soils. However, where capital-intense farming is justified, even initially poor peats can be reclaimed to highly productive soils.

ACID SULPHATE SOILS

N. van Breemen

Properties

Most acid sulphate soils occur in the tropics, in low-lying coastal land formerly occupied by mangrove swamps. Their most important characteristics are a field pH of below 4, owing to the oxidation of pyrite to sulphuric acid, and a generally high clay content. If samples of the pyrite layers are air-dried in the laboratory, the pH may drop by a further 2 units. Other properties such as organic matter content and cation exchange capacity may vary widely.

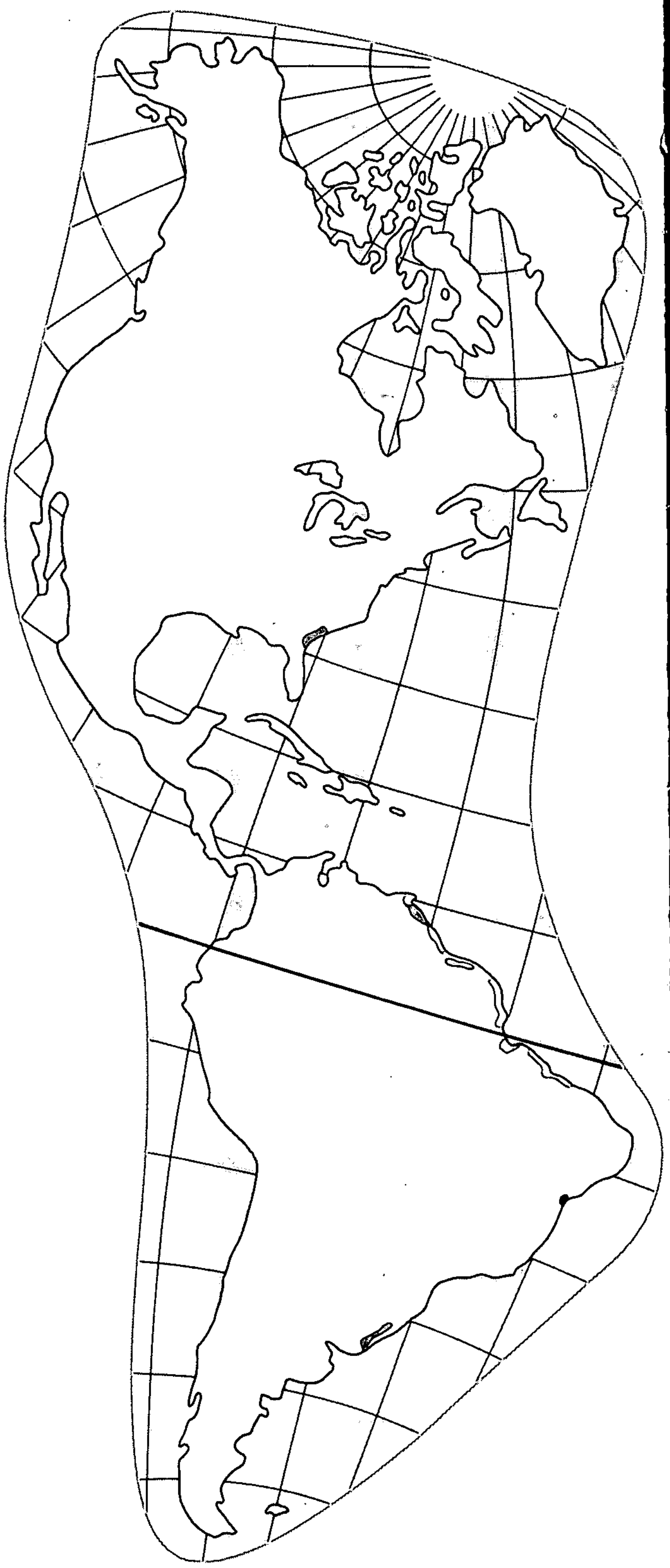
Potential acid sulphate soils have a near-neutral pH but become strongly acid upon drainage and oxidation. The total area of actual and potential acid sulphate soils is rather small: about 10 million hectares are known to occur in the tropics, and the world total probably does not exceed 14 million (Table 3, Figure 3).

In addition, some 20 million hectares of coastal peats, mainly in Indonesia, are underlain by potential acid sulphate soil. In spite of their relatively limited areal extent, planners and agronomists have been paying much attention to acid sulphate lands, mainly because of their apparent suitability for agriculture (especially for rice) and their often close proximity to good to excellent agricultural land.

Table 3.
Regional distribution of acid sulphate soils (based on data from FAO/UNESCO Soil Map of the World; length of growing periods according to FAO Agro-Ecological Zones Project, Rome).

Region	Area(10^6 ha)	Area (million ha) per length of growing period			
		<90 days	90–180 days	180–300 days	> 300 days
Africa	3.7	0.4	0.7	1.5	1.1
Near and Middle East	–	–	–	–	–
Asia and Far East	6.7	–	0.2	5.1	1.4
Latin America	2.1	–	0.1	0.8	1.2
Australia	–	–	–	–	–
N. America	0.1	–	–	–	–
Europe	–	–	–	–	–
World total	12.6				

Figure 3.
Worldwide distribution of acid sulphate soils (adapted from FAO/UNESCO Soil Map of the World 1971–1979).



■ dominant
covering 30–100% of the soil association

□ not dominant (associated)
covering 20–30% of the soil association

▨ not dominant (inclusions)
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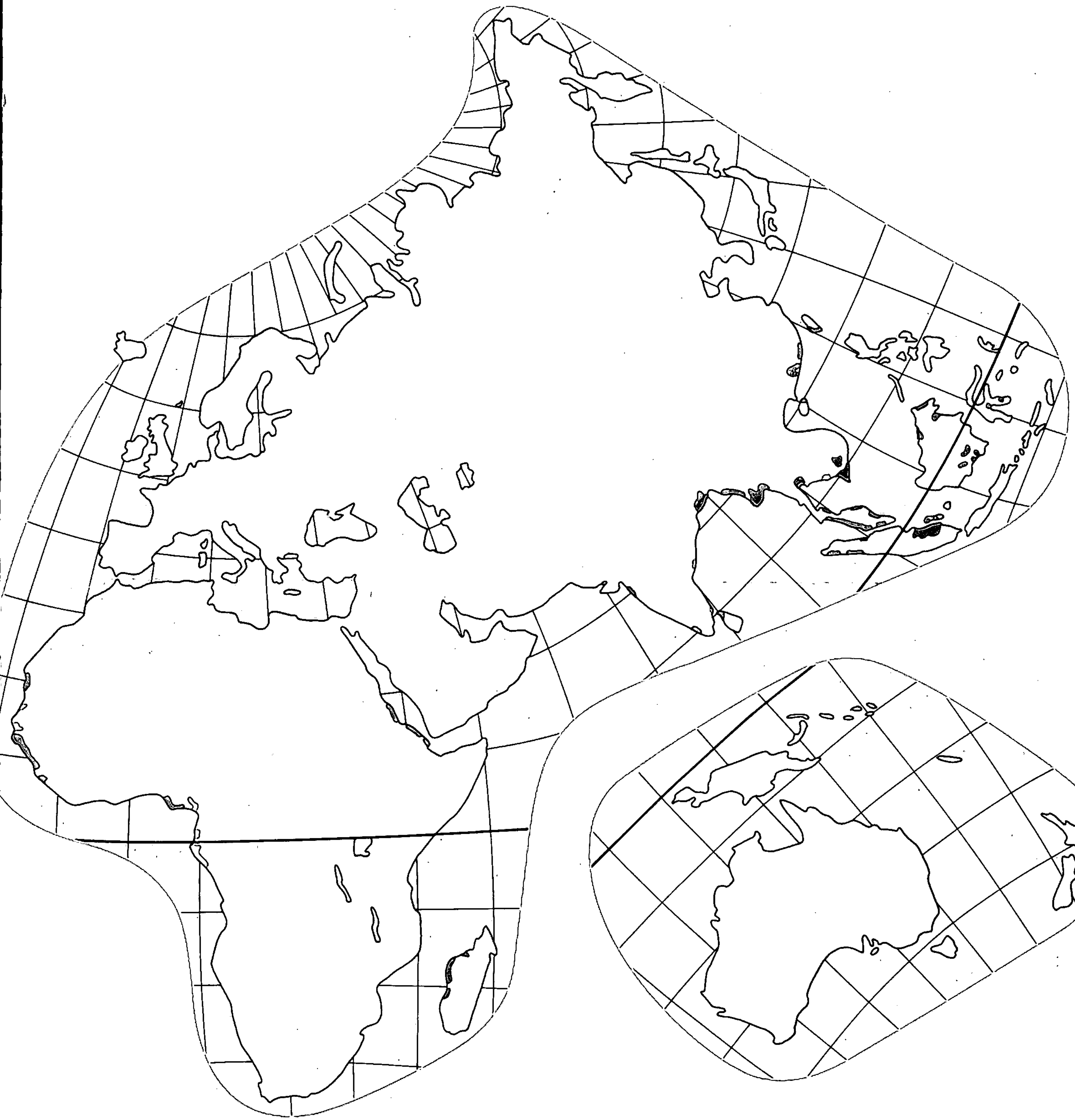
source: FAO/UNESCO soil map of the world



Problems

The growth of most dryland crops on acid sulphate soils is hampered by the toxic levels of aluminium and the low availability of phosphorus. Toxic levels of dissolved iron plus low phosphorus are the most important adverse factors for wetland rice. In the near-neutral potential acid sulphate soils (Sulfaquents, Sulfic Fluvaquents), high salinity, poor bearing capacity, uneven land surface, and the risk of strong acidification during droughts are the main disadvantages.

Young acid sulphate soils (Sulfaquepts) in which the pyritic substratum occurs near the surface are often more acid than those soils (Sulfic Tropaquepts, Sulfic Haplaquets) in which this horizon is found at greater depths. Acid floodwater generated in large swamps with very acid Sulfaquepts, as in Vietnam, may adversely affect crops grown on adjacent better land.

Present land use

Most potential acid sulphate soils are under natural vegetation (mangrove swamps, tidal marshes) or are used for mangrove forestry (charcoal, nipa thatch, nipa sugar). Fishponds in potentially acid land can be fairly productive, provided that the pyritic substratum is not exposed and oxidized. In climates with a marked dry season, potentially acid swamps can be used for salt extraction. In some tidal swamps where the surface water is seasonally fresh, tidal swamp rice is grown on cleared mangrove land.

Young, shallow, acid sulphate soils are commonly left uncultivated, although with good water management they can be used with some success for oil palm and rice as they are in Malaysia. In Thailand, older acid sulphate soils are used extensively for broadcast deepwater rice, giving low to moderate yields. Droughts and sudden deep flooding, however, are probably at least as much to blame for lower rice yields on these older soils as are phosphorus deficiency and aluminium toxicity.

Possibilities

The older, deeply developed acid sulphate soils require no specific reclamation measures, and can be greatly improved by good fertilizer application, moderate dressings of lime (1–5 ton/ha) and, probably most important, good water management.

In reclaiming or improving potential and young acid sulphate soils two diametrically opposite approaches are possible:

- Pyrite and soil acidity can be removed by leaching after drying and aeration, and
- Pyrite oxidation can be limited or stopped and existing acidity inactivated by maintaining a high watertable.

Additional liming and fertilization, especially with phosphorus, are usually necessary with either method. Liming alone, while technically and agronomically feasible, is always prohibitively expensive on these very acid soils.

The first method, combined with leaching by seawater has been used with some success in experiments in Sierra Leone, and these efforts have attracted considerable attention. The method can only be applied under specific conditions: close proximity to the sea, an appreciable tidal range and strongly contrasting wet and dry seasons. Even then, costly annual dressings of lime are still necessary, and no instances of a successful large scale application have been reported.

A far more elaborate reclamation method involving leaching to remove acidity is being applied in the Mekong Delta of Vietnam. There, strongly acid soil, often with a shallow pyritic substratum, is excavated to make 3–5 m wide ridges separated by ditches 2 m deep and 3 m wide. Although pyrite oxidation and leaching must be extremely rapid under those conditions, it may still take 5 to 10 years before the soil is suitable for crops other than the highly acid-tolerant pineapple, which is planted immediately after the ridging.

Clearly, such reclamation measures are usually uneconomic. Most of the available experience from field and laboratory experiments shows that leaching is too slow to remove an appreciable and relatively immobile fraction of the soil acidity (mainly adsorbed aluminium, adsorbed sulphate and basic sulphate such as jarosite) from most of the soil within an acceptable time. However, leaching is often necessary to remove accumulations of soluble acid salts (Al-Fe-Mg sulphates) near the surface of rice fields on young acid sulphate soils after a dry fallow, and to remove acid surface water generated above flooded, reduced acid sulphate soils. This is usually done in the course of the growing season by lateral drainage of surface water after repeated wet tillage.

The second reclamation method, maintaining a high watertable to stop pyrite oxidation and to inactivate existing soil acidity, has the advantage that its effects are usually noticeable within two years or so. This is especially true in young acid sulphate soils that are generally high in organic matter. Upon waterlogging, soil reduction caused by microbial decomposition of organic matter lowers acidity and may cause the pH to rise rapidly to near-neutral values. The method is particularly suitable with rice cultivation, but even in oil palm plantations in Malaysia, maintaining a shallow watertable has given far better results than deeper drainage with intensive leaching.

The crucial factor is, of course, the availability of fresh water for irrigation. Large-scale engineering schemes for reclaiming potentially acid, and usually strongly saline, coastal swamp are rarely economic.

In the Muda irrigation project in Malaysia, where patches of Sulfaquepts occur among better soils, improved water management and intensive irrigation have dramatically increased the productivity of these highly acid soils.

So, unless sufficient fresh water is available and other prerequisites for good water management exist, potential acid sulphate soils and young, strongly acid sulphate soils should not be reclaimed, but are better left for other types of land use (conservation, forestry, fisheries and, sometimes, salt pans). If fishponds are constructed on such land they should be kept shallow, because deep excavation will cause the water to turn toxic. The injudicious reclamation of seemingly suitable land in coastal swamps by excluding salt water through diking and by excavating fishponds has led to the destruction and abandonment of thousands upon thousands of hectares of mangrove land in southeast Asia and Africa. The less toxic and deeper developed older acid sulphate soils are moderately suitable for rice and can be improved by sound agronomic practices, such as growing adapted cultivars and applying phosphorus. By intensifying water and soil management, including dry season irrigation, the productivity of these soils for rice will increase and they can probably be made productive for a wide variety of annual and perennial dryland crops.

PLANOSOLS

R. Brinkman

Properties

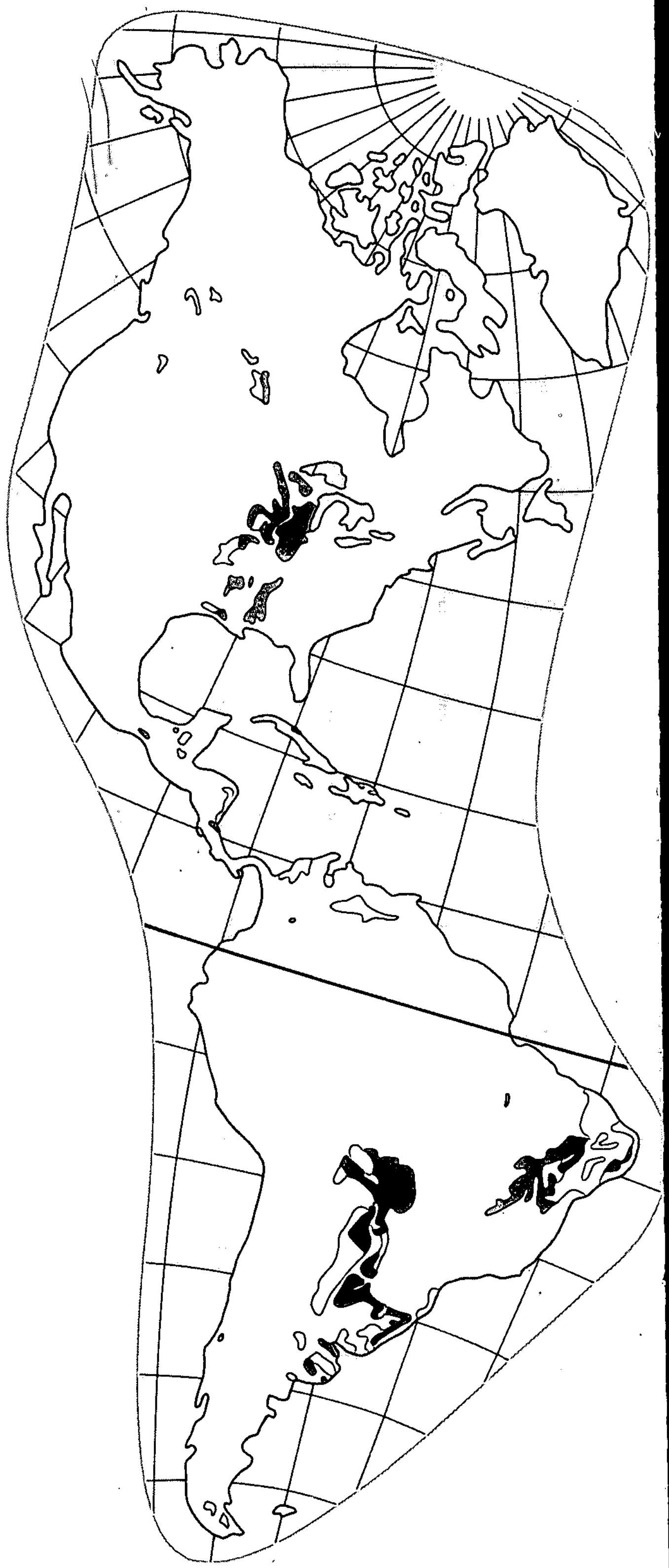
Planosols and other acid, seasonally wet soils occupy some 151 million hectares worldwide, mainly in subhumid and wetter climates with a pronounced alternation between wet and dry seasons. The largest expanses of planosols occur in Latin America (767 million hectares); see Table 4, Figure 4.

They are most extensive on nearly level parts of the landscape above normal river levels, but may also occur in river plains, for example those of the Brahmaputra (Bangladesh) or the Luena (Zambia). These soils are also found in less strongly seasonal climates where a nearly level land surface combined with a low hydraulic conductivity of the subsoil or substratum causes periodic waterlogging.

Planosols have lower clay contents in their surface horizons than in their slowly permeable deeper horizons. Other acid, seasonally wet soils generally show the same trend but less markedly. The activity of the clay fraction (cation exchange capacity and moisture retention) is normally lower in the surface soil than in deeper horizons.

In extreme cases the upper soil horizons have a very low structural stability; if silty, they may be like concrete in the dry season and like a very

Figure 4.
Worldwide distribution of planosols (adapted from FAO/UNESCO Soil Map of the World 1971-1979).



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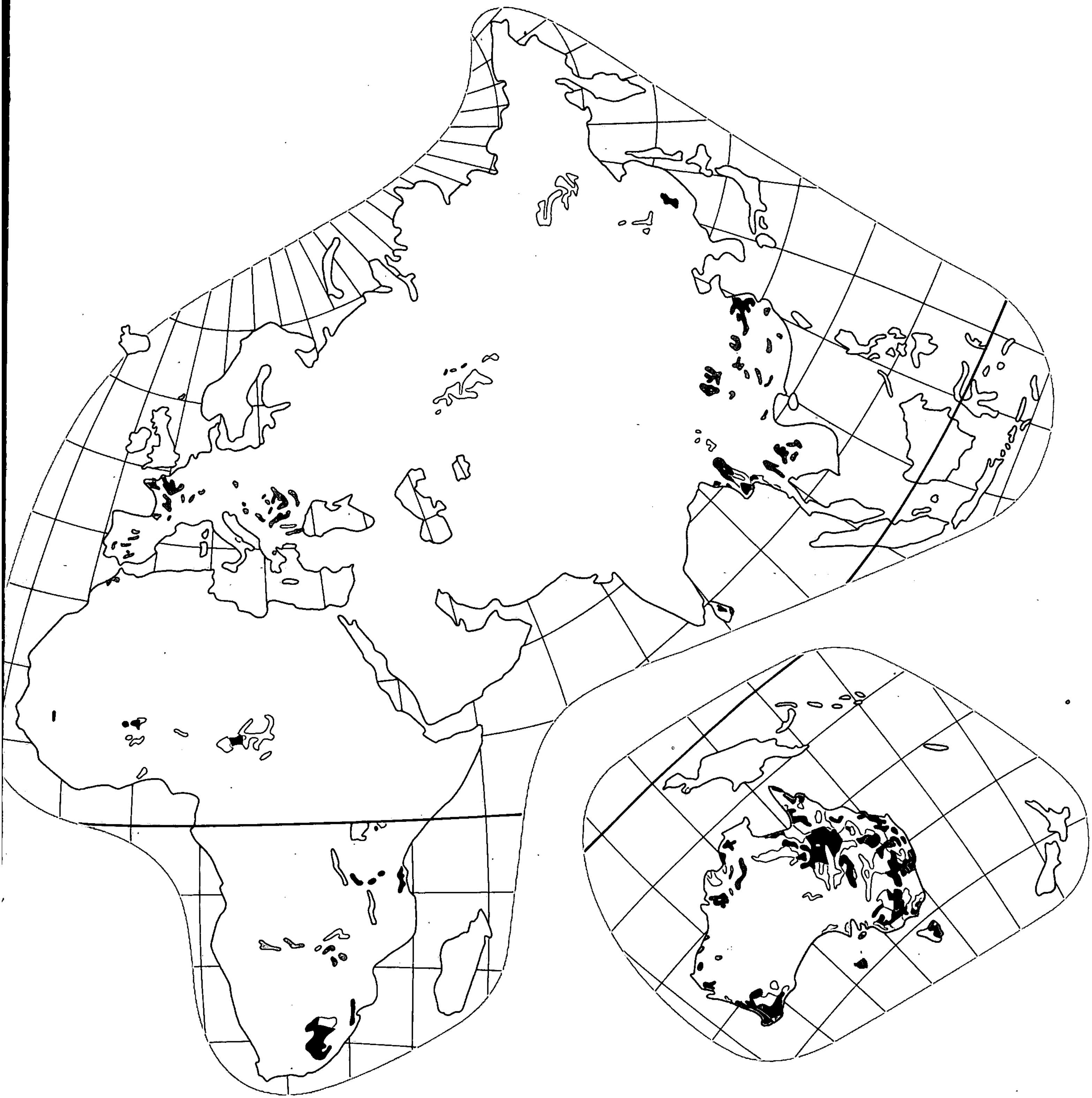


Table 4.
Regional distribution of planosols (based on data from FAO/UNESCO Soil Map of the World; length of growing periods according to FAO-Ecological Zones Project, Rome).

Region	Area (10^6 ha)	Area (million ha) per length of growing period			
		<90 days	90–180 days	180–300 days	> 300 days
Africa	15.9	8.1	5.5	2.3	–
Near and Middle East	–	–	–	–	–
Asia and Far East	2.7	0.2	0.7	1.6	0.2
Latin America	67.2	7.7	23.0	32.5	4.0
Australia	49.3	–	–	–	–
N. America	12.3	–	–	–	–
Europe	4.0	–	–	–	–
World total	151.4				

heavy syrup, with extremely low bearing capacity, when waterlogged or inundated in the wet season.

When dry, the sandy topsoil may be very compact but is not cemented.

Problems

Plants tend to root shallowly in these soils. The seasonal waterlogging that hampers the growth of most crop plants and trees alternates with drought conditions, whose severity depends on local climatic conditions. This drought period also depresses yields and limits the choice of crops, or may prevent dry-season crop production where no irrigation water is available.

Under natural vegetation, less strongly developed acid, seasonally wet soils generally have porous upper horizons that are at least moderately stable. The stability appears to be due to slight cementation by silica rather than to organic matter, iron oxides, or clay. The porous structure is easily destroyed by cultivation, particularly by puddling, and is not easily re-established. Puddling over the years produces a very compact traffic pan, which retains some bearing capacity when wet. Once the traffic pan has been disturbed by deeper cultivation, even though this was done when the soil was dry, its bearing capacity when waterlogged becomes very low, so that even buffaloes used as draught animals tend to sink.

Besides these problems directly due to their peculiar hydrology, these soils tend to have a low natural fertility level. They are normally strongly acid but without aluminium toxicity in the surface horizons; deeper horizons may be toxic to the roots of sensitive plants, such as certain citrus cultivars, particularly when fertilizers are applied. Even slight salinity, as occurs in patches on the 'low terrace' in northeast Thailand, for example, may bring about aluminium toxicity at the soil surface, which hinders the germination of most crop plants.

Where the parent material of the soils already contains low-activity clays, the still lower activity and low content of clay in the surface horizons of planosols severely limit their capacity to retain added fertilizers. If liming is practised to eliminate aluminium toxicity, the dosage needs to be carefully established since it is easy to overlime these soils to or above neutrality, which may induce new nutrient deficiencies. Besides the usual low fertility level of these strongly weathered soils, there may be silica deficiency, as observed in paddy rice cultivation in northeast Thailand (KAWAGUCHI and KYUMA 1969).

Where planosols are less strongly weathered and occur, for example, over a swelling clay substratum as in southern Tanzania or on the Madhupur and Barind tracts in Bangladesh, the cation exchange capacity of the surface soils in normally adequate and there is no silica deficiency.

Present land use

Planosols are used for a variety of purposes, partly depending on the climate. However, they generally support a lower intensity of use than soils which, under the same climate, have less extreme alternations in hydrology (i.e. are either better drained, or have a better moisture supply in the dry season).

Some planosols only support a sparse grass and sedge vegetation with scattered bushes; other areas are under grass, grass with scattered trees, or forest, depending on the amount and distribution of rainfall. Growth rates of forest, in terms of wood production, are commonly half to less than a third of those on well-drained soils with similar parent materials and environment.

In the tropics, particularly in southeast Asia, and in the Far East, large areas of these soils produce a single crop of paddy rice on bunded fields inundated during the rainy season. Some trials to produce dryland crops on the same land with irrigation during the dry season have met with little success; the soils seem better suited to a second crop of paddy rice with dry-season irrigation and fertilization. In temperate climates, planosols are mainly used as grassland or for arable crops such as wheat or sugarbeet. Yields are relatively low, mainly owing to waterlogging in winter or spring and drought in dry summers. Locally, as near Rome, some of this land has been abandoned by farmers and used for housing, with occasional minor disasters due to flooding in unusually wet winters.

Possibilities

Strongly developed planosols, whether with silty or with sandy surface horizons, are probably best left in their present state, without efforts at improvement.

Where paddy rice is currently being grown, a supply of irrigation water would make double-cropping possible. The provision of irrigation might be economic if yields are improved by the simultaneous introduction or increased use of more productive cultivars and of fertilizers. The soils should be allowed to dry out at least once a year, however. This should prevent or minimize possible micro-element deficiencies or toxicities due to extreme reduction. Some of these soils may require applications of more than just the three major fertilizer elements before high yields can be attained: their low fertility level may prove difficult to correct.

High productivity of dryland arable crops or grass is very difficult to achieve on these soils without great fluctuations from year to year. Narrow drain spacings would be required because of the low hydraulic conductivity of the subsoil or substratum, but the disturbance during their installation tends to cause the soil structure to deteriorate. Thus, the resulting yield increases, if any, are small. Besides oxygen deficiency in wet periods, both excessive soil density and aluminium toxicity may hinder or prevent roots from entering the subsoil. Experiments in several European countries, spanning a number of years after drainage and deep loosening of the subsoil, with and without deep placement of calcium carbonate, have failed to show conclusive economic results.

In climates with long drought periods and short infrequent spells of waterlogging, as in southern France or Italy, irrigation of grassland or of arable crops grown in the dry season may hold promise. However, wherever temperature regimes are favourable for rice, paddy rice cultivation would probably be more profitable.

SALINE AND SODIC SOILS

R. Brinkman

Properties

Of the various problem soils in the world, saline and sodic soils occupy by far the largest area (323 million hectares). They are most widespread in arid and semi-arid climates, but also occur in more humid climates, especially in coastal areas. Australia has the largest area of saline and sodic soils: 85 million hectares, followed by Africa: 70 million hectares and Latin America: 59 million hectares (Table 5). Figures 5 and 6 show the worldwide distribution of saline and sodic soils, respectively.

Saline soils are defined by the electrical conductivity of saturation extracts of certain soil horizons (FAO 1978) or by their soluble salt contents. The salt content may fluctuate, depending on evaporation and rainfall, or on irrigation history. Sodic (formerly called 'alkali') soils have at least 15 per cent exchangeable sodium that may decrease their physical stability. Many have a poor structure and a very low hydraulic conductivity. Most are alkaline, with a pH above 8.5 owing to the presence of sodium carbonate. Some are almost neutral and a few – mainly those not in arid and semi-arid zones – are acid. Some soils are both saline and sodic. There is no clear definition of sodic soils as such because the distinctions made by FAO (1974) and the SOIL SURVEY STAFF (1975) include a requirement that there is evidence of clay illuviation. In acid sodic soils and in sodic vertisols the 15 per cent limit is unsatisfactory because these soils do not show evidence of the characteristic low stability and poor structure except at appreciably higher proportions of exchangeable sodium.

Table 5.
Regional distribution of saline and sodic soils (based on data from FAO/UNESCO Soil Map of the World; length of growing periods according to FAO Agro-Ecological Zones Project, Rome).

Region	Area(10^6 ha)	Area (million ha) per length of growing period			
		<90 days	90–180 days	180–300 days	> 300 days
Africa	69.5	56.8	8.4	3.6	0.7
Near and Middle East	53.1	51.0	1.6	0.5	0
Asia and Far East	19.5	13.3	4.0	1.7	0.5
Latin America	59.4	32.2	9.2	12.7	5.3
Australia	84.7	–	–	–	–
N. America	16.0	–	–	–	–
Europe	20.7	–	—	–	
World total	322.9				

Problems

The salts or exchangeable sodium in saline and sodic soils hinder crop growth. For efficient crop production they must therefore be leached from the root zone. This procedure is itself problematical because in most regions with these soils, irrigation water is scarce. Some soils that are more difficult to reclaim may require several times as much irrigation water as others.

If the land is not carefully levelled before basin irrigation is carried out, any variations in the microrelief (of the order of 5–10 cm) will cause considerable differences in the amounts of irrigation water entering the soil. Saline and sodic patches may thus persist or develop rapidly, even in land originally non-saline. It may take up to two years before an area is satisfactorily levelled. For other methods of irrigation the land need not be so scrupulously level, but all methods need considerable care to ensure that the irrigation water is uniformly distributed.

Under favourable circumstances, most of the water applied to saline soils percolates through and removes the salts. However, if evaporation is high or the hydraulic conductivity of the soil is low, much more water must be applied to ensure percolation. Savings can be made if the irrigation water can be applied during seasons with a low evaporation rate. Alternatively, the sustained infiltration rate may be increased by measures such as cultivation, deep ripping, gypsum application, or a combination of these. A further problem arises if the irrigation water is itself saline. The more saline the water, the longer it takes to leach the salts.

It should be noted that there is a critical level of the evapotranspiration/percolation ratio beyond which the soil cannot be reclaimed. This level depends on the ratio between the desired soil salinity level and the salinity of the irrigation water, and on the leaching efficiency of the soil.

In strongly structured soils or in soils with many large pores, the water moving along the cracks and pores hardly comes into contact with the soil and therefore removes fewer salts. To overcome this problem the large pores in the surface horizon can be destroyed by cultivation measures such as harrowing or puddling.

In principle, the sodium carbonate present in many sodic soils can be leached. However, the associated high proportion of exchangeable sodium can only be leached after it has been replaced by other cations. These may be supplied in different ways, for example from gypsum dissolving in the percolating water, or from calcium carbonate or clay minerals dissolved in acid. These amendments (i.e. calcium salts or acids) may be added to the irrigation water or applied to the soil surface.

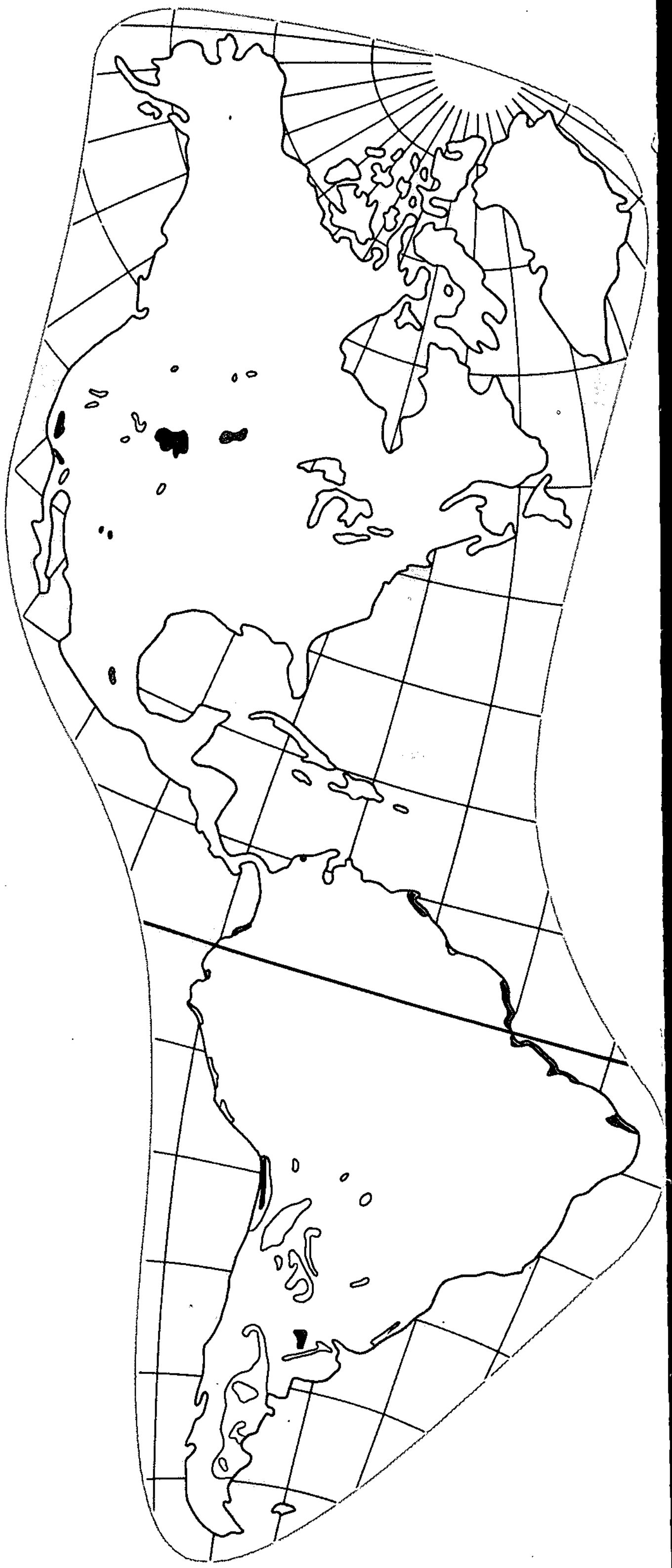
More water is required to leach a sodic soil than a saline soil. This is because the usual chemical amendments are less soluble than the usual salts and because sodic soils are generally less permeable than saline ones. If the percolation rate is much lower than the evapotranspiration rate, the amendment may have to be incorporated into the surface horizon and more applied superficially.

Sodic soils with a silt loam or silt texture and a homogeneous system of very fine interstitial pores have a very low saturated conductivity and leaching water barely moves through them under gravity. Water moves predominantly upwards under the influence of evaporation, and therefore any salts and sodicity accumulate near the surface. Moreover, there is virtually no air-filled pore space after water application until a fairly high suction is reached, at which point the soil material becomes almost dry. At present, the reclamation and use of such soils (which usually occur in tidal river deltas) for irrigated agriculture is neither economically nor technically feasible.

Even where the present permeability of the subsoil is good, reclamation of sodic soils is problematical. During the reclamation process the composition of the cations in the percolating water below the reclamation front is nearly in equilibrium with the original exchangeable cations, and may be mostly sodium. As a result, the total salt concentration may become too low to maintain flocculated conditions and the deeper horizons may coalesce into a virtually impermeable mass. To avoid this, saline reclamation water may have to be used in the early stages. Amendments supplying divalent cations are needed throughout the reclamation process.

Saline and sodic soils can be reclaimed by lowering the watertable. Even when the problems of initial reclamation have been overcome, further problems can arise. Renewed salinization or sodification can occur. Soils with a low capillary conductivity (e.g. clayey soils) can usually be drained satisfactorily by installing a system of ditches or pipe drains, 1.5 to 2.5 m deep. However, soils with a higher capillary conductivity (e.g. silty soils) must be drained deeper to prevent salinization or sodification, unless the groundwater quality is good. Deep drainage in areas receiving a strong inflow of groundwater from adjacent regions poses economic problems. The installation of a system of ditches or pipes may then be prohibitively expensive unless the soil is intensively cropped without long fallow periods. Tube well drainage could provide a solution but, economically, there is the problem of either disposing of the effluent or, if possible, using it for irrigation

Figure 5.
Worldwide distribution of saline soils (adapted from FAO/UNESCO Soil Map of the World 1971–1979).



■ dominant
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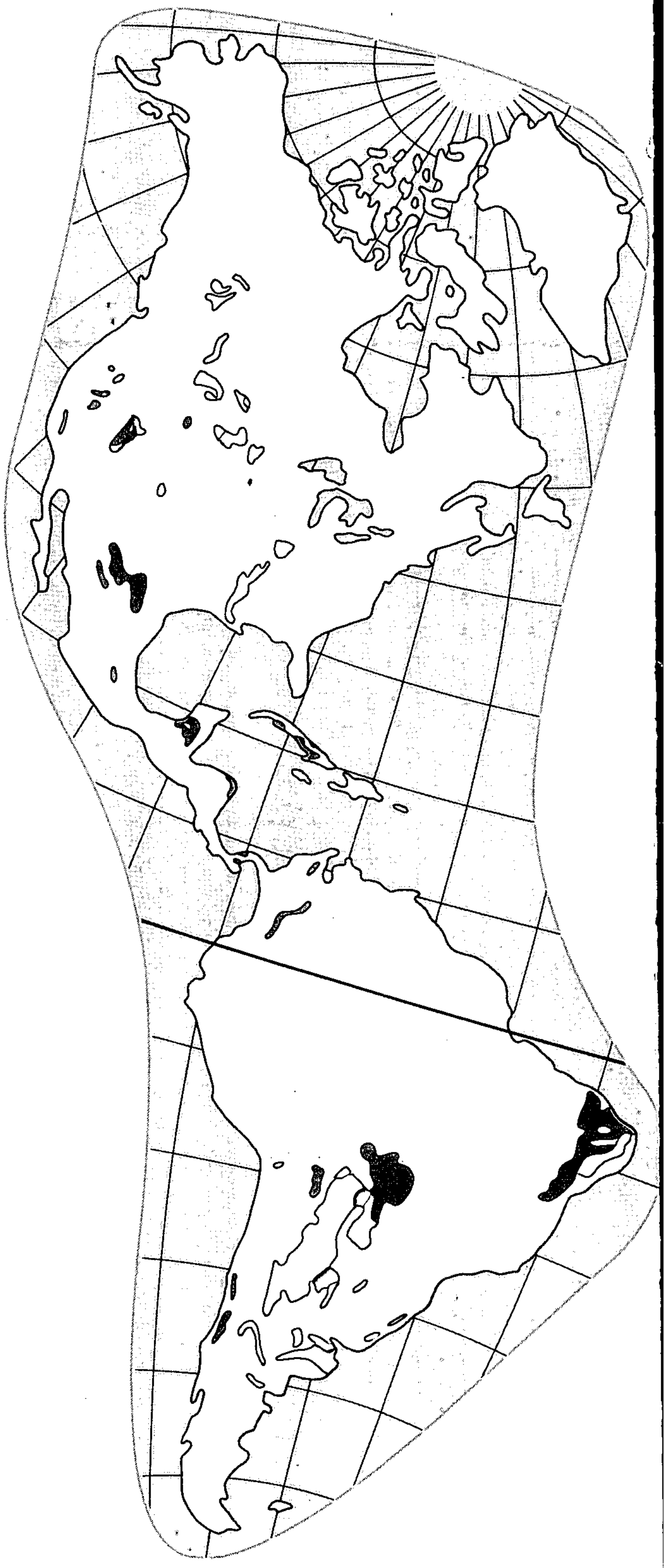
source: FAO/UNESCO soil map of the world

Figure 6.
Worldwide distribution of sodic soils (adapted from FAO/UNESCO Soil Map of the World 1971–1979).



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source: FAO/UNESCO soil map of the world

after it is mixed with good quality surface water.

Present land use

Saline soils are mostly left in their natural state or used for extensive grazing. Fine fighting bulls are raised on the saline coastal lowlands of France and Portugal. Also sheep, goats, and camels graze the salt-tolerant vegetation of saline soils in semi-arid zones.

Depending on the salt content and depth of the salty horizon, cereals of a certain tolerance may be grown under rain-fed conditions: barley is often grown on saline soils in mediterranean and semi-arid climates; a less tolerant crop grown on these soils is wheat. With irrigation, rice is sometimes grown on fine-textured saline soils. Before the rice plants are transplanted the saline soil is repeatedly flooded and drained to promote the diffusion and removal of salts from the topsoil to permit a moderate yield of the salt-tolerant paddy-rice varieties.

On sodic soils, land use is more varied, depending on the chemical properties of the topsoil and on the drainage conditions. In the depressed areas of the Argentinian Pampa for instance, extensive areas of sodic soils with topsoils rich in organic matter (FAO: Mollic Solonetz) support good herds of beef cattle. In California, after the dense natric subsoil has been broken, irrigated citrus plantations are established.

But generally speaking, saline and sodic soils are either used in a highly adapted and mostly very extensive way, or are reclaimed with high capital inputs, thus requiring intensive, high yielding land use types to make such land improvements economically justified. A good example of this is the reclamation of saline soils in coastal Peru with subsurface drainage for high yielding sugarcane.

Possibilities

When assessing the potential of a saline soil, the depth to which a soil is salt-free is far more important than the degree of soil salinity. Similarly, in a sodic soil, structural stability and hydraulic conductivity are more relevant than the proportion of exchangeable sodium present.

Often the highest returns to irrigation water are obtained not by land reclamation but by increasing the cropping intensity on the best non-saline non-sodic land. Removing surface salinity on otherwise good land also gives very high returns. This requires an initial application of irrigation water to leach the salts, followed by a regular water supply to sustain intensive cropping.

If irrigation water is still available, the second priority is to reclaim moderately or strongly saline land with a good hydraulic conductivity.

Even with adequate hydraulic conductivity, sodic soils generally give much lower returns per unit irrigation water, since they require more water for their reclamation.

FINE-TEXTURED ALLUVIAL SOILS

L. J. Pons

Properties

Marine and fluviatile alluvial plains often include large areas of fine-textured (at least 35 per cent particles $<2\mu$) clay soils within depths of about 80 cm. These azonal soils may occur in any climate and their characteristics vary greatly, partly in association with the prevailing climate.

Fine-textured fluvial soils are found in the backswamps of river floodplains which, under natural conditions, are covered by fresh-water forest and are regularly inundated with river water containing fine sediment. Vast areas of marine coastal and estuarine plains are also partly or completely comprised of fine-textured clay soils formed by tidal inundations of salt marshes and mangrove by saline to brackish water containing fine silt.

The chemical composition of fluviatile fine-textured soils in river backswamps depends on the kind of sediment carried by the rivers. Soils poor in minerals are common in the floodplains of small rivers in humid tropical climates. Such soils have low contents of weatherable minerals and organic matter, their clay minerals are kaolinitic, and they are very poor in macronutrients and in many micronutrients. Their pH and cation exchange capacities are low and they have a high proportion of adsorbed aluminium ions sometimes causing aluminium toxicity. Of the fine-textured fluvial soils in the tropics, those richest in weatherable minerals are developed on sediments deposited by rivers that originate in volcanic or recently uplifted mountains and later flow through arid areas. Most rivers in temperate climates receive their sediments from catchment areas with young, shallow soils on mainly physically weathered rocks or loess. They normally transport sediments rich in organic matter and minerals. Those rivers in temperate or boreal climates that flow over old granitic or gneissic shields supply sediments that are relatively poor in weatherable minerals.

In contrast with fluvial fine-textured soils, the marine variety shows less variability in nutrient contents and contains potassium, magnesium, calcium, sulphate, and sometimes phosphorus. In coastal plains and estuaries the river sediment is not only enriched by contact with sea water but is also usually mixed with sediments transported from the sea floor. As a result, nutrient contents are increased, carbonates are sometimes added, and clay minerals are mixed.

The chemical composition of sediments in the humid tropics is poorer than that of similar sediments in arid or temperate climates. The low organic matter contents of both humid and arid tropical marine sediments, as compared with those of temperate and boreal marine sediments, is a major disadvantage of the soils developed on these sediments.

Problems

The main adverse physical conditions of the fine-textured fluvial and marine soils can be low structural stability, low permeability, poor workability and difficult conditions for root growth. The properties critical to agricultural development and use of these soils are organic matter contents, free carbonates, iron oxide contents, active clay minerals, and the amounts of adsorbed Na Ca and Al cations.

Tropical alluvial sediments have low primary organic matter contents and thus give rise to soils with a poor structural stability. Sediments in temperate and boreal zones are characterized by high to very high organic matter contents, well mixed with the clay particles, Although some of the organic matter is mineralized during ripening, enough remains to contribute to a favourable structural stability. Nearly all the fine-textured soils in humid temperate areas are noncalcareous: this also decreases structural stability. In the sediments of floodplains and some coastal plains in humid tropical areas, low contents of iron oxides are common and this also contributes to poor structural stability.

Large areas of very fine-textured alluvial clay soils are virtually impermeable for water and roots. In the humid tropics these dense marine and fluvial soils have low organic matter and iron contents, contain kaolinitic clays, and lack carbonates. In the humid temperate areas the dense marine 'knip' soils lack carbonates and are saline. In arid zones the dense soils are very saline and have low organic matter contents. Desalinization is a difficult and slow process.

Fine-textured soils are often difficult to work because they have a narrow workable moisture range. Insufficient drainage is also a restricting factor in the flat areas where these soils occur.

Present land use

In temperate climates the fine texture and poor drainage conditions of some alluvial soils formerly restricted their use to extensive grassland. As techniques of drainage and empoldering improved, it became possible to reclaim fine-textured fluvial and marine soils.

In humid temperate climates, however, large-scale rain-fed crop cultivation has not developed because of the difficulties of seedbed preparation, the problems of harvesting in wet conditions, and the poor drainage of these soils. Only some fine-textured alluvial soils with very favourable physical properties (high organic matter and iron contents, active clays and free carbonates – as in the Dutch IJsselmeerpolders; or high organic matter and iron contents and high amounts of adsorbed aluminium ions – as in the deacified acid sulphate *gyttja* soils of Sweden) are used for intensive crop rotations and economic production. The majority of the fine-textured alluvial soils, showing medium to poor qualities are successfully used for intensive forms of grassland.

Semi-humid or semi-arid temperate climatic conditions, however, restrict the possibilities for grassland and favour crop production (which is now the most widespread land-use, even on physically poor soils).

In the humid tropics, people also learnt better land-use practices and in the course of several thousands of years very extensive grazing on alluvial soils was replaced by different forms of wet-land rice cultivation. With the exception of very acid soils, all kinds of fine-textured alluvial soils are now used for extensive and intensive rice cultivation. Few rain-fed crops are cultivated because of drainage and management problems. Tree crops are only grown on the alluvial soils of best quality, where the soils show high structural stability and the drainage problems can be overcome. A wide range of fruit trees is successfully cultivated with or without irrigation in the coastal plains of Java, Guyana, Malaysia, and Thailand.

In arid areas where no crops can be grown without irrigation, poor structural stability, resulting in impermeability, difficulties of root penetration, and the need for intensive drainage, militates against crop production.

Possibilities

Protection from flooding (diking) and drainage are the two main priorities for the reclamation of fine-textured alluvial soils, if necessary combined with proper application of lime and/or gypsum to improve structural stability and permeability. If the soil conditions of the sub-soils are favourable, deep ploughing may give considerable improvement.

Prior to any land improvement, soil surveys are needed to ascertain the relevant soil properties for the main land-uses. These surveys should include permeability measurements both in saturated and unsaturated conditions. Research on the way the permeability and the structural stability vary as well as on future subsidence under planned land-use is necessary.

In The Netherlands, new research on the fine-textured fluviatile backswamp soils and marine 'knip' soils has shown that intensive drainage combined with land use such as modern grassland on these already ripened soils may, in the long term, lead to slightly improved topsoil development, better subsoil structures, and an increase in permeability. Processes such as progressive physical ripening, slight desalinization, and an increase in biological activity contribute to these results.

Physically unripe or partly ripe fine-textured alluvial clay soils will develop cracks that may considerably improve their permeability. Especially in the tropics, however, low organic matter contents and the presence of low activity clays, sometimes combined with salinity may cause both low cracking and structural instability, resulting in impermeability upon ripening. In these cases wet rice cultivation may be the solution for economic land-use. Possible development of sulphate acidity is another danger, although moderate production of acids by oxidation of pyrite both with or without the presence of carbonates may improve structural stability. More research on these soil processes is needed.

Subsidence accelerated by reclamation and by improved drainage of the alluvial soils will affect the drainage systems and may necessitate extensive land levelling if wet rice is to be grown.

In arid and semi-arid climates, salinization is a hazard, and irrigation must always be accompanied by sufficient drainage, even for wet rice production. If peaty topsoils occur in alluvial plains in the tropics, and the alluvial soils are permeable enough for tree crops, these layers should not be burnt because they will help maintain the soil structure. With wet rice cultivation, however, the peat layers should be burnt to obviate management difficulties.

When research indicates that it seems dangerous to reclaim fine-textured marine alluvial soils (because of their salinity,impermeability, or proneness to acid sulphate development), alternative land-use should be considered such as grazing, fishponds, shrimp production, mangrove cultivation for timber, and wild life conservation.

OUTLOOK FOR THE FUTURE

With the exception of the fine-textured alluvial soils, whose regional extent is not yet known, the world-wide distribution of the problem soils discussed in this article is presented in Table 6. Their total is an estimated 987 million hectares.

Of the 1,000 million hectares of alluvial soils known to exist in the world (FAO: Fluvisols and Gleysols), let us assume that half of them (or 500 million hectares) are fine-textured. Adding this to the 987 million hectares of Table 6, we arrive at a total of 1.5 billion hectares of soils with problems of water management.

Much has been learned about how to make some of these soils productive, but much still remains to be done. The technique of reclaiming saline and sodic soils is well advanced. Some peat soils have been used successfully for centuries. For acid sulphate soils, research is still needed to find a reclamation method that is at the same time economically feasible. Little is known about the many soil processes that come into play in the reclamation of fine-textured alluvial clay soils.

With the future world food situation causing more and more concern, the vast area of problem soils is posing a challenge to land and water specialists.

Table 6.
Worldwide distribution of a number of problem soils. (million hectares).

Type of soils	Vertisols	Peat soils	Acid sulphate soils	Planosols	Saline and sodic soils
Africa	105.0	12.2	3.7	15.9	69.5
Near and Middle East	5.7	0	0	0	53.1
Asia and Far East	57.8	23.5	6.7	2.7	19.5
Latin America	26.9	7.4	2.1	67.2	59.4
Australia	48.0	4.1	0	49.3	84.7
N. America	10.0	117.8	0.1	12.3	16.0
Europe	5.4	75.0	0	4.0	20.7
World total	258.8	240.0	12.6	151.4	322.9

Acknowledgement

The authors of this article would like to thank the FAO Agro-Ecological Zones Project for kindly allowing them to include in their tables previously unpublished data on the extent of the zones with different growing seasons. They also gratefully acknowledge the permission granted them by the the FAO World Soil Resources Office to publish information on the extent of soils in Europe. And finally they wish to thank Mr. N. Konijn for his excellent work in compiling the maps accompanying the article.

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Groundwater resources management research

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Importance of groundwater

Groundwater is one of the earth's most widely distributed natural resources. It has been a source of water supply since the dawn of recorded history. Many great economic developments have been made possible through the use of groundwater. For many towns and villages, industries, and irrigated farms, it is the *only* source of water. In spite of its importance for mankind, it is surprising that only 1,200 km^3 of the 3,100 km^3 of water mankind uses yearly comes from groundwater reservoirs (AMBROGGI 1978). The remaining 1,900 km^3 comes from surface water stored in lakes and streams. Agriculture is the greatest consumer – 2,400 km^3 a year – followed by industry with 500 km^3, and other human activities with 200 km^3. To supply these needs it has long been the policy to construct dams, behind which the water of streams backs up to form surface water reservoirs. These reservoirs not only supply water but also serve to control floods and to produce hydro-electric power.

The future prospects for any large expansion of dam reservoirs, however, seem to be limited for the following reasons:

- few sites are suitable for dams and dam reservoirs because of their geological, geomorphological, and topographical conditions; most suitable sites already have a dam
- the residence time of the water stored in dam reservoirs rarely exceeds a year, which offers inadequate protection against rainfall deficits that last longer than a year
- the annual costs of regulating surface water by a dam reservoir now amounts to about US $ 0.10 per m^3 (op. cit.)

As against this:

- the storage capacity of many groundwater reservoirs generally far exceeds that of dam reservoirs
- the life-time of a groundwater reservoir is much longer than that of a dam reservoir
- groundwater can usually be recovered and used at the site where it is needed
- groundwater has a nearly constant temperature and chemical composition – the average price of recovering groundwater is about US $ 0.02 per m^3 (op. cit.)

Under these circumstances it is not surprising that more and more interest is nowadays being shown in groundwater. The world's groundwater resources still offer great prospects for development. An estimated 4.2 million km^3 of it is stored in the upper 800 m of the continents, which represents 97 per cent of all the readily available fresh water in the world. The quantity stored in lakes and streams is only 0.126 million km^3.

If we further consider that, unlike oil and minerals, groundwater is a renewable resource, with 12,000 km^3 of water being cycled through underground reservoirs annually and only one

Groundwater recovery along the borders of Lake Chad by means of a shadoof. The water is used to irrigate a wheat crop. The container is made of reeds.

tenth of that being recovered, it is evident that great possibilities for this natural resource lie ahead.

The management problem

During the last decades, one of the greatest advances in man's attitude towards groundwater has been the realization that groundwater is not a utility to be used with mere indifference; like every natural resource, groundwater must be wisely managed. It is now understood that the world's No. 1 raw material must be carefully protected against over-exploitation, and diligently safeguarded from contamination by pollutants or salt water. Undesirable side effects such as depletion of the groundwater reservoir, deterioration of the water quality, and subsidence of the land must be avoided.
Primarily, groundwater resources management is governed by one of three concepts:

- the safe-yield concept
- the mining concept
- the dual-purpose concept

The safe-yield concept

The safe yield of a groundwater reservoir is that yield of groundwater that can be recovered without causing long-term declines of the watertable. This concept is not new. MEINZER (1932) in the United States of America was one of the first to identify it. He wrote: 'The most urgent problems in groundwater hydrology at the present time are those relating to the rate at which rock formations will supply water to wells in specified areas – not during a day, a month, or a year, but perennially'.
The idea behind the safe-yield concept is that groundwater abstraction from a basin should be limited to the average annual rate of the basin's recharge, thus keeping the basin essentially in hydrological equilibrium. In some humid regions, like The Netherlands, where agriculture depends on both rainfall and a shallow groundwatertable, groundwater pumpage is under strict control. Added to this is the awareness that even a slight decline of the watertable due to groundwater pumpage can destroy certain valuable ecosystems.
Operating a groundwater reservoir on the basis of the safe-yield concept frequently means that large quantities of groundwater in static storage are not used. Such a policy allows these immense quantities to be held for future emergency use, for example, when the region in question suffers from a long period of drought or when, for whatever reason, surface water supplies are interrupted.
In the last decades the safe-yield concept has fallen somewhat into disuse. The reason is that it has not been possible to separate from the safe

Animal power used for recovering groundwater in the Konya Plain, Turkey.

yield the various practical aspects of groundwater recovery methods, distribution, jurisprudence, and costs. TODD (1959) therefore re-defined the safe yield of a groundwater basin as 'the amount of water that can be withdrawn annually without causing an undesirable influence in the basin'.

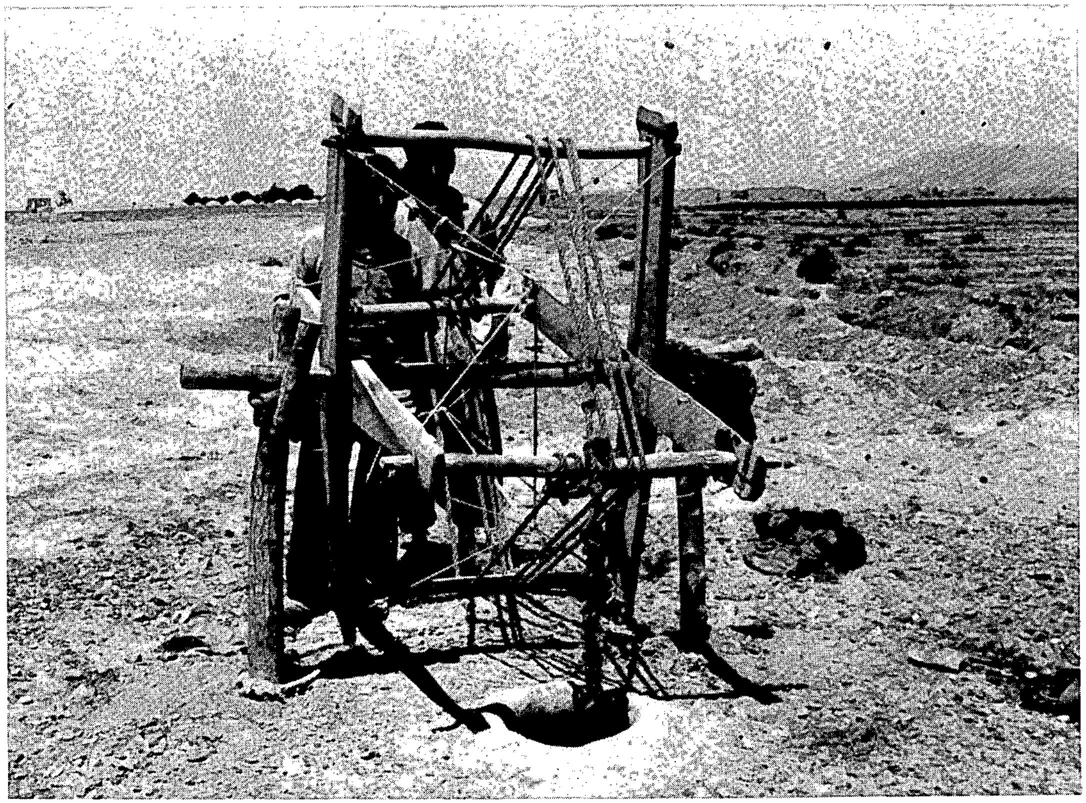
The mining concept

If the safe-yield concept were to be applied in arid and semi-arid regions where the natural recharge of groundwater basins is meagre, hardly any groundwater could be recovered. In such regions, therefore, groundwater is sometimes deliberately mined. The quantities of groundwater that can be mined are known as the secular reserves and are located between the undisturbed watertable and the maximum economic pumping lift.

The idea behind the mining of groundwater is that once a prosperous economy is established, more expensive schemes such as water importation, desalinization, or the re-use of waste water can then be introduced. Here, we can speak of an economic safe yield, which is the yield that can be withdrawn without the danger of the wells drying up before an adequate tax base for the more expensive water supplies has been established. In the United States of America, regions that have developed economically using groundwater for initial water supplies are the Los Angeles Coastal Plain, the Texas High Plains,

Artesian well in the Konya Plain, Turkey.

Traditional way of qanat building in Iran.



and the Central Arizona Plain (HALL and DRACUP 1970).

For the economic development of arid regions AMBROGGI (1978) advocated the mining of groundwater. He refers to thirty years of experience in northern Africa where a single year of unusually heavy rainfall, which can be expected at least once in 15 years, can replenish aquifers that have been mined in previous years, even those in which the watertable drawdown is as much as 10 to 20 m. In some regions it seems possible to deplete a groundwater reservoir for as long as 40 years and still have it refilled by natural processes.

The dual-purpose concept

Mining of groundwater in some places serves a dual purpose: (1) to lower the watertable and thus prevent soil salinization, and (2) to make more water available for irrigation. Examples of this technique are well known from the United States of America where the introduction of irrigation with surface water led to steadily rising watertables. Vast areas became waterlogged and had to be drained artificially. When several of these conventional drainage systems did not function properly because the drain pipes silted up, large numbers of wells were drilled and pumped to lower the watertable. With the extra water thus obtained the area of irrigated land could be substantially enlarged. At present about one third of all irrigation water used in the United States is groundwater.

Other examples of groundwater mining for a dual purpose are known from the Soviet Union (Uzbekistan en Kazakstan) and Pakistan where in the Indus Plain thousands of tubewells have been drilled.

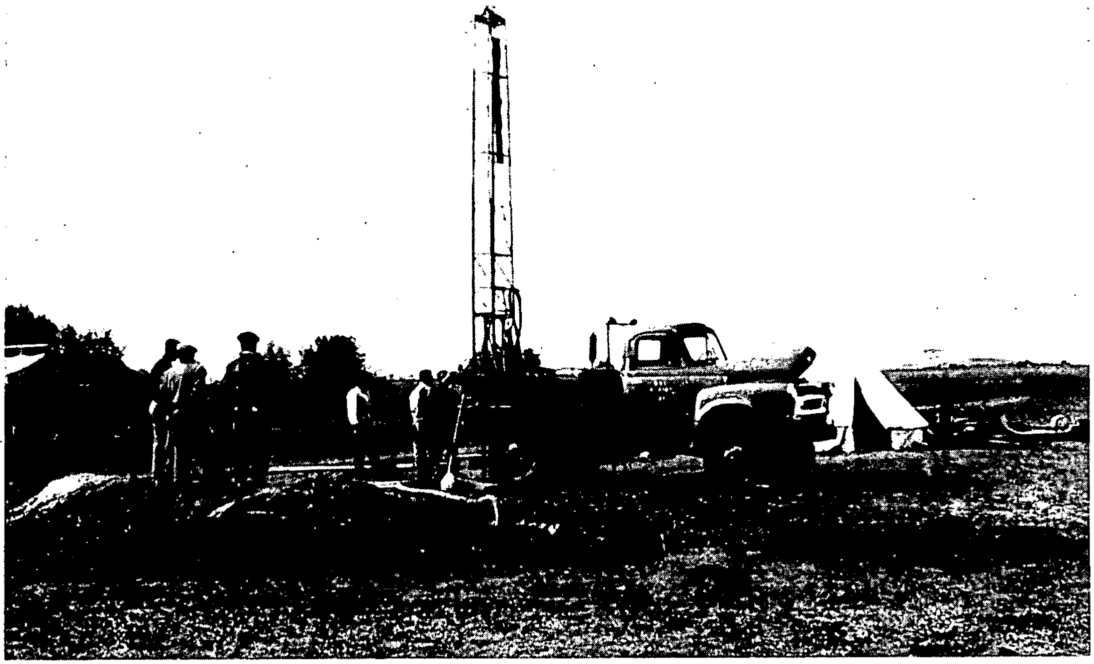
In general this concept of groundwater resources management is only possible when the groundwater is of good to fair quality or, if this is not so, when the groundwater can be mixed with good quality surface water. It goes without saying that this technique requires an efficient irrigation service capable of properly operating and maintaining the well system.

Groundwater quality

The vast expansion in population, industry, and irrigation (approximately 200 million ha were under irrigation in 1978), has led to a vastly increased waste disposal. Until recently large surface water bodies but also groundwater reservoirs have served as virtually infinite waste disposal sinks. Since the residence time of groundwater in underground reservoirs is long, there is growing concern about the groundwater resources becoming irreversibly polluted by the underground disposal and transport of contaminants.

The problem of contaminant transport in groundwater systems can perhaps best be illustrated by

Modern way of waterwell drilling.



the present search for a geologic disposal site for radio-active waste.

The slow movement of groundwater is a factor in its favour when the contaminants are biodegradable or are bacteria and viruses that decompose or die with time. During the long residence time underground the water may be freed of these undesired substances. After groundwater has moved a sufficient distance from the source of pollution, the concentration of contaminants may be so reduced by dispersion and other attenuation factors that the groundwater eventually becomes pollution-free. How far the groundwater must move depends on the type of aquifer material, the flow velocity, the type of contaminant, etc. A sandy aquifer, for example, is a much better purifier than an aquifer of cavernous limestone or laterite through which the water may flow so fast that no natural purification takes place. For situations where the water quality change can be measured by the amount of total dissolved solids, GROVE (1976) has presented methods of quantifying chemical reactions for rate and equilibrium controlled ion-exchange reactions and radioactive decay.

In the last decades salt-water intrusion into coastal aquifers has become a serious issue in groundwater resources management (TODD 1953). If coastal aquifers are pumped beyond the safe-yield, watertables will decline and sea water will flow inland (Figure 1). For every metre of watertable drop, the salt water will rise 40 m. Coastal aquifers must therefore be carefully managed to preserve the depth of the interface between fresh water and salt water.

A common method of protecting fresh groundwater in coastal areas is to recharge the groundwater artificially to create a fresh water ridge along the coast and thus form a barrier against intruding sea water. Solutions to the problem have been presented by HENRY (1959), BEAR (1960), BEAR and DAGAN (1962,1964), and GLOVER (1964). For predicting the movement of salt water fronts in coastal aquifers, PINDER and COOPER (1970) presented a numerical model. KASHEF (1976) reviewed the advances made in the theory of salt water intrusion.

The intrusion of salt water into fresh water aquifers is not confined to coastal regions. It may also occur in groundwater basins far inland where fresh water overlies salt water or where a local body of fresh water occurs amidst salt water (Figure 2). When a well in the fresh-water zone is pumped the interface between fresh and saline water will rise. If the upconing salt water reaches the bottom of the well, brackish or salty water will be pumped. BEAR and DAGAN (1968) presented a formula for the rise of the cone below the centre of the well.

The high crop yields obtained by modern agriculture require an intensive use of fertilizers and pest-

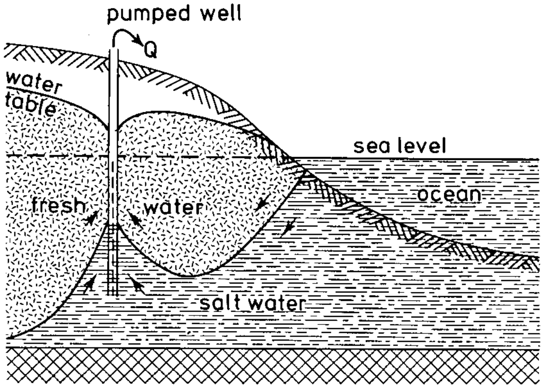


Figure 1.
Fresh and salt groundwater near a coast. Effect of overpumping: salt groundwater enters the well.

icides. Some of these chemicals may move downward with deep percolation water and contaminate the groundwater. In arid zones, deep percolation water from irrigated land, in addition to transporting salts from the consumed water, also leaches soluble minerals from the soils and underlying rocks as it moves to and through the groundwater reservoir. The leaching also picks up soluble solids that are constantly being produced by chemical weathering. Moisture and carbon dioxide, originating from decaying vegetation, greatly accelerates chemical weathering in irrigated areas. As most irrigation systems produce significant quantities of deep percolation water, it is obvious that unless natural drainage is maintained or a portion of the salty water evacuated in some other way, the underlying groundwater will deteriorate and eventually salinize completely.

Land subsidence

Movements in the earth's surface can be one of the undersirable consequences of heavy groundwater pumping. Subsidence of as much as 10 m and horizontal movements of several metres have been recorded in some regions. Subsidence is largest where water level declines are greatest and aquifers and aquitards (layers of low permeability) are thickest and most compressible. Horizontal movements produce cracks and fissures in the earth which may damage buildings, roads, bridges, and pipelines. BOUWER (1978) refers to examples in the United States of America where groundwater pumping for irrigation in the San Joaquin Valley, California, has caused a total subsidence of 8.5 m and subsidence rates of as much as 0.55 m a year; a subsidence of 40 to 60 cm per 10 m watertable drop was measured at some places. Parts of Mexico City have subsided about 8 m since heavy groundwater pumping began in 1938.

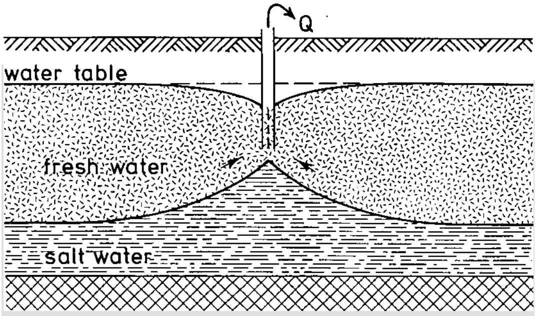


Figure 2.
Fresh groundwater overlying salt groundwater in an unconfined inland aquifer. Upconing of salt water beneath a pumped well.

Groundwater models

In the complex business of managing groundwater resources, major advances have been made in the last 25 years. These advances became possible through the development of models of some sort, the most important of which will now be reviewed (PRICKET 1976).

Analytical models

Groundwater flow problems can be described by differential equations that are obtained by combining Darcy's equation and the continuity equation. These partial differential equations, which relate the flow, hydraulic head, and aquifer parameters, are in a sense models of the particular conditions defined. Hence we may speak of *mathematical models and call this approach* to groundwater flow problems the analytical method. Many of the analytical solutions were developed between 1950 and 1960. The books of POLUBARINOVA-KOCHINA (1962), BEAR (1972), VERRUIJT (1972), HUISMAN (1972), and others are good references that present the available analytical formulas, their solutions, and applications.

Viscous fluid models

The analogy between the differential equations for steady two-dimensional flow of groundwater and those for two-dimensional flow of a viscous fluid between closely spaced parallel plates has led to the use of viscous fluid models (Hele-Shaw models). Variations in an aquifer's hydraulic conductivity or transmissivity are accounted for by varying the interspace of the parallel plates. Fluid is supplied or withdrawn from the model interspace at rates proportional to the groundwater flow. The fluid levels between the plates represent the hydraulic heads of the aquifer. This type of model is used in either a vertical or a horizontal position. In vertical position the model can be used to study the seepage under a dam, sea water intrusion into coastal aquifers, drainage towards ditches, etc. In horizontal position the model is used for the study of the regional effects of pumping, recharge, and flow in multi-layered aquifers (SANTING 1958; COLLINS *et al.* 1972).

An advantage of models of this kind is that they are capable of simulating a free surface and the interface between fresh and salt water for both steady and unsteady flow conditions.

Electric models

The analogy between the flow of groundwater and the flow of electricity has led to the use of electric analog models. Models have been developed on the basis of two systems:

- the continuous system
- the discrete system

In the first, a conductive medium (electrolytes or conductive paper) is used to model the aquifer properties. In the second the aquifer properties are modelled by an assemblage of discrete electric elements comprising a network. These elements represent certain portions of the aquifer which are interconnected through nodes. The system consists of an array of electric resistors or an array of electric resistors and capacitors (PRICKET 1975).

The continuous systems were developed in the 1950s and were used mainly for steady-state flow problems in homogeneous aquifers with irregular boundaries. The discrete systems, which were developed between 1950 and 1965, had a much wider field of application. They were used to analyse non-homogeneous and anisotropic aquifers under either steady or unsteady state situations. They thus allowed the study of problems of variable pumping, recharge, evapotranspiration, surface-water/groundwater relationships, and non-linear effects of unsaturated flow.

By the mid 1960s the electric analog was fully developed and was being used routinely by many groundwater hydrologists. Its great advantage was and still is that it is capable of solving large and complex problems involving tens of thousands of nodes, as in three-dimensional flow problems. Disadvantages are that the problem of the common watertable case, in which the aquifer's transmissivity is a function of the depth of flow, has not been satisfactorily solved and that some of the equipment needed for the model is rather costly.

An electric analog model can solve a set of simultaneous equations almost instantaneously after source, sink, and boundary values are impressed on the model. But the process of measuring node voltages, making mass balances, and preparing watertable contour maps takes a great deal of time. Digital computers are fast in processing data but slow in solving large numbers of simultaneous equations, particularly when the equations are non-linear. For this reason the 'hybrid system', which combines a small digital computer and an electric analog model, was developed.

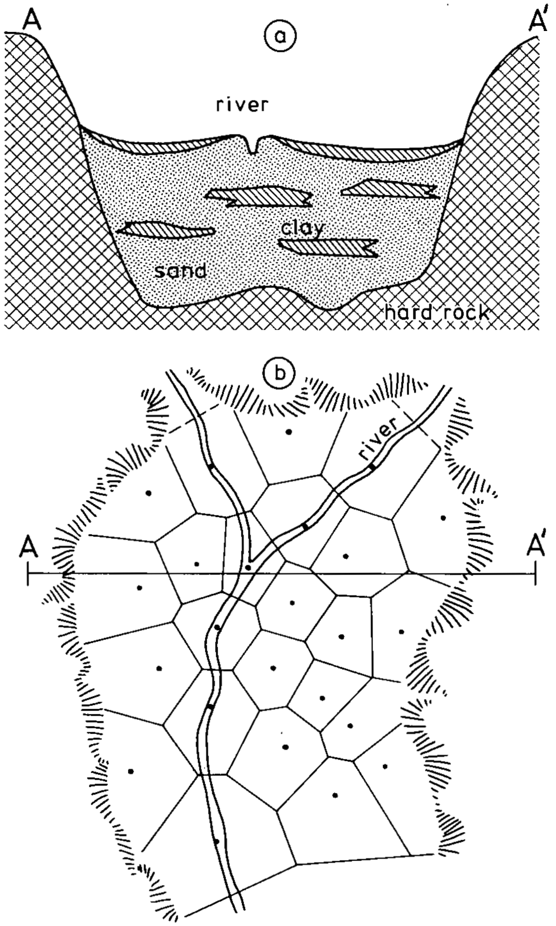


Figure 3.
Example of an asymmetrical finite difference network over a river valley: (a) cross section (b) plan. The valley walls of massive hard rock are impervious (zero flow boundary). The river is a head-controlled boundary.

Numerical Models

Partial differential equations that describe the flow of groundwater are not easy to solve when the boundary conditions are complex. In the last decade two powerful techniques, developed many years earlier in other branches of science, were put to use in finding approximate solutions to complex groundwater flow problems. These techniques are:

- the finite differences method, and
- the finite element method

The *finite differences method* was developed by RICHARDSON (1910). For more than simple conditions, however, his method was time-consuming and was therefore little used. In a later stage SHAW and SOUTHWELL (1941) again drew attention to this method. But it was not until the appearance of the digital computer, which could handle the tedious arithmetic, that the method became popular. FAYERS and SHELDON (1962) and TYSON and WEBER (1964) were among the first to develop a finite difference code that allowed a computer study of the spatial distribution of hydraulic heads in aquifers.

The method requires that the flow domain be discretized by placing a network of squares or polygons over it (Figure 3). The Darcy equation is then used to develop finite-difference expressions for the flow in each square or polygon.

The difference between the inflow and outflow of each square or polygon equals the change in storage over the considered time step. An additional term is included in the equation to account for external inputs or outputs of groundwater (recharge from rainfall, irrigation water, seepage from streams or canals, or discharge by pumpage from wells, drainage towards streams, evaporation, etc. (Figure 4). There is one equation for each node with the head as an unknown. Usually an implicit (backward-difference) method is used to calculate these unknowns.

Just how powerful this technique is can be understood from the work of FREEZE (1972) who developed a digital model that can handle up to 10,000 nodes in variable grids and is capable of solving two or three-dimensional, steady or unsteady, and saturated or unsaturated flow in heterogeneous or anisotropic aquifers of varying shapes and with a wide variety of time-variant boundary conditions. In areas where accurate solutions are desired, the spacing between the nodes can be made smaller than where less accurate solutions will suffice. The accuracy or reliability of the solutions depends less on the method than on the input data, which can be very uncertain. These uncertainties cause a much greater error in the results than the method itself.

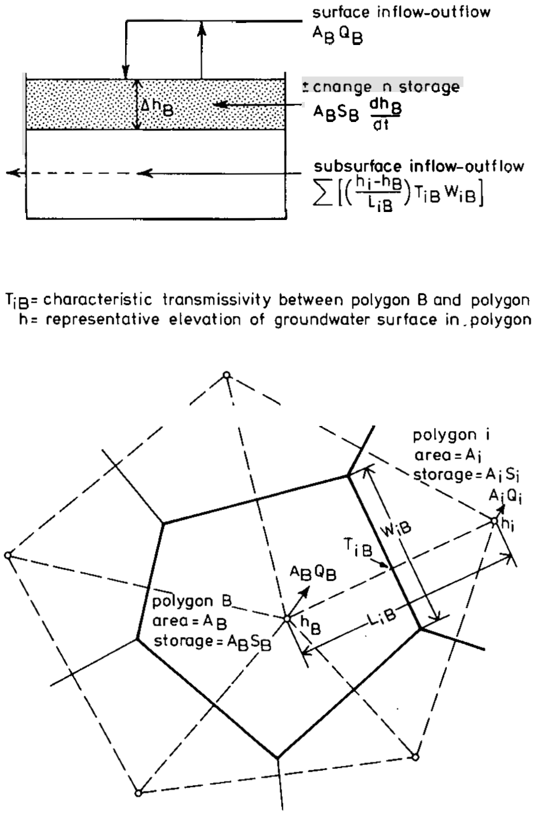


Figure 4.
Scheme of a polygon with the different flow components.

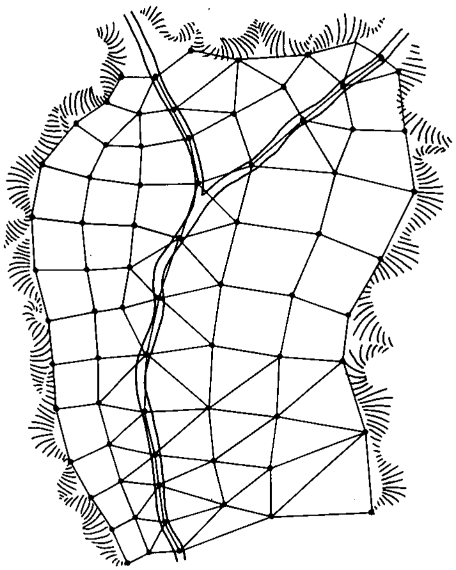


Figure 5.
A finite element network superimposed on the same river valley as shown in Figure 3.

The *finite element method* was developed by COURANT (1943) in a study to find solutions to problems of equilibrium and vibrations, although, he did not yet use the term 'finite elements'. The technique received its name from TURNER et al. (1956) in a study that approached a continuous structure by 'finite elements'. In a later stage the method was rediscovered when it was found to correspond closely with 'variational calculus'. It was ZIENKIEWICZ et al. (1966) and ZIENKIEWICZ (1971) who played a decisive role in indicating the possibilities offered by the technique in solving different kinds of groundwater flow problems.

In the finite element technique the differential equations are also replaced, but now by a 'functional'. A functional can be regarded as some sort of an energy equation that must be minimized. The flow system is considered to be a general system of energy dissipation for which the head solution is found as the head distribution that minimizes the rate of energy dissipation (BOUWER 1978).

The finite element method also requires that the flow domain be discretized, i.e. divided into a number of sub-areas, or 'finite elements', that can have different shapes: triangles or quadrilaterals, joined by nodes at the boundaries of each element. The elements should be as disordered and non-uniform as possible to prevent solutions from going into preferred directions (Figure 5).

As with the finite difference method, a number of simultaneous equations, readily solved by a computer, are produced.

Although the finite element method is somewhat less transparent than the finite difference method, which is fairly simple and straightforward, it is nowadays used to solve a wide variety of groundwater flow and quality problems. MARINO (1976), for example, used both the finite difference and the finite element techniques to solve the problem of contaminant transport in groundwater systems. For a review of the literature on the use of the finite element technique in modelling contaminant transport in groundwater, the reader is referred to GRAY (1976).

Model calibration

In spite of the advances made in developing numerical and electric analog models of extensive groundwater basins, many of these models often fail to serve as reliable planning and management tools. There are several reasons for this:

- oversimplification of the groundwater system
- erroneous assumptions underlying the model
- uncertainties in the hydrologic input data
- scarcity of and uncertainties in the values of the basin's parameters.

All these factors may be responsible for the wrong predictions of watertable behaviour that these simulation models may produce. Any kind of model must be verified or validated if the predictions or generated data are to have a meaning. Verification thus means that the model must be proved to be true. This is commonly done by 'history matching' which means that unknown or uncertain parameter values, such as permeability and storativity, are determined by the closest fit of measured and calculated watertable elevations.

In large groundwater basins, the aquifer permeability or transmissivity and storage coefficient are known from a few sites only. If these parameters were found from, say, properly conducted pumping tests they may be sufficiently accurate and reliable. Similar values, however, are also needed for all the nodes of a network or all the sides of the squares or polygons, but these data are usually not available.

Recent developments in solving this calibration or 'inverse problem' have been the introduction of various automatic and semiautomatic calibration techniques. One of these is the 'indirect' approach, which is merely an automatic trial and error procedure that tries to improve an existing estimate of the parameters in an iterative manner until the model response is sufficiently close to that measured in the real aquifer. Another approach is the 'direct' one. It treats the model parameters as dependent variables in a formally posed 'inverse' boundary value problem of the Cauchy type (NEUMAN 1976; NEUMAN and KAFRI 1976).

CHEN et al. (1974) and CHAVENT et al. (1975) applied optimization techniques to obtain a detailed adjustment of the transmissivity map of oil basins. YEH and YOON (1976) introduced a procedure based on scattered observations of head variations within the aquifer. This technique seeks to improve the method of subdividing a given inhomogeneous aquifer into piecewise homogeneous subregions, each subregion being characterized by a single parameter. In regions where the parameters are accurately determined, subdividing is refined. Coarse grids are developed where parameters are ill-determined.

By using one or more of the above techniques it is possible to find a good set of aquifer parameters. 'Good' means that if we feed these values into the computer, the computed nodal watertable fluctuations may be very close to those measured in the field. But this does not necessarily mean that we have now proved that the model is 'true' and that it can unconditionally be used as a predictive tool for planning purposes.

Apart from the aquifer parameters, the net recharge term may also contain uncertainties or severe errors. The net recharge term is the algebraic sum of all the external flows, which in most groundwater basins are not known precisely. The net recharge from rainfall and/or irrigation is often ill-determined, or at worst just a guess, and so are the losses from evaporation and pumpage.

A verified model need therefore not necessarily be a true model. Used as a predictive tool, as all these groundwater simulation models commonly are, they may have limited value.

In referring to the difficulties that arise in an attempt to fix criteria for when a model is verified, NAYLOR and FINGER (1967) quote the philosopher Karl R. Popper, who suggested that we concentrate on the degree of confirmation of a model rather than whether it has been verified. Popper stated: 'If in a series of empirical tests of a model no negative results are found but the number of positive instances increases, then our confidence in the model will grow step by step'.

Where do we go from here?

The tremendous progress made in developing different types of models is one of the main achievements in the management of groundwater resources over the last 25 years. The progress in this field far surpasses that in field techniques, although no one would wish to deny the great advances made in the use of satellite photographs, radio-isotope analysis for age determination of the groundwater, and geophysical methods for exploring aquifers and aquitards and determining their porosity.

To-day's problem, however, is not a lack of appropriate mathematical tools, but a lack of quantitative field data that allow groundwater basin parameters to be identified. For the near future there is a need to improve the methods of data collection and data analysis of groundwater problems.

The economic effects of alternate depletion rates and pumping patterns in a groundwater mining situation need further study. More thought must also be given to the effect that the use of land for agriculture, urbanization, forestry, grazing, and road construction has on water yields, water quality, flow regimes, and groundwater recharge; erosion, flooding, and sedimentation need more consideration. Link-ups between physical, non-physical, and economic models are still rare and may have a great potential.

The hydrogeology of low-permeable layers (aquitards) needs further attention in view of the severe problems resulting from contamination of groundwater and from land use practices. Little is known to what extent confining layers serve effectively as retardation zones for toxics or other contaminants. Finally, there is still a need for practical guidelines in planning the use and management of coastal aquifers.

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Methods and models in surface water hydrology

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Introduction

In today's society, water is controlled and regulated to serve a wide variety of purposes. The problem of matching society's demand for water with its availability in nature involves various disciplines. One of these is water resources engineering, which comprises the planning, design, and construction of facilities to control and utilize water. Table 1 shows the main fields of water resources engineering and the specific questions encountered within them.

The role of hydrology in water resources engineering is to provide answers to these questions. It must supply data on the time and spatial distribution of water over the land areas of the earth. Hydrology is concerned with three major sources of water: water in streams, water in lakes, and water in underground storage. This article deals only with water in streams. (For groundwater hydrology, see article by de Ridder in this book).

In considering the flow of water in streams, the hydrologist considers the following characteristics:

- the annual flow and its long-term variability
- the annual distribution of flow
- the flood flow: its volume and peak discharge
- the low flow: its volume and duration

The first two items characterize the average long-term potential quantity of water that is available from a basin; the second two characterize the extreme conditions that the hydrologist may need to know in design studies of water resources projects. For example, to determine the capacity of spillways, he must know the flood flows, whereas for irrigation or the generation of hydropower, he must know the low flows, and especially their durations.

For the quantitative asessment of these extremes, the hydrologist has many methods and models at his disposal. Their development and use in surface water hydrology will be reviewed in this article. But first an explanation will be given of how a hydrologist arrives at his design discharge.

Probability: a base for design

The majority of hydrological phenomena are processes subject to the laws of chance. Runoff being one of these processes, periods of low flows alternate with periods of high flows, with changes in the magnitudes of these flows from year to year. From low to high, any magnitude of discharge has a certain probability of occurrence and the higher or the lower the discharge, the less likely it is to occur.

In water resources projects one is often interested in estimating the probability of an exceedance. An exceedance is an event with a magnitude greater than a certain pre-set value; it does not necessarily mean a flood; it can also refer to the severity of a drought. Because one never has an

Table 1.
Main fields of water resources engineering (adapted from LINSLEY 1979).

	Control of excess water				Conservation				
					(quantity)				(quality)
Studies required	Flood mitigation	Storm drainage	Bridges, culverts	Sewerage	Water supply	Irrigation	Hydro power	Navigation	Pollution control
How much water is needed?	...	...	...	...	x	x	x	x	x
How much water can be expected?									
Minimum flow	...	...	...	x	x	x	x	x	x
Annual flow	...	...	...	x	x	x	x	x	x
Flood peaks	x	x	x	...	x	x	x	x	
Flood volume	x	x	...	...	...	...	...	...	x
Groundwater	...	x	...	x	x	x	...	...	x

infinite set of historic runoff records (known as the 'population'), one has to work with a sample of these records. A sample may range from a few years to several decades, but seldom longer. The finite length of samples makes it impossible to derive the probability of exceedance from them, but one can derive the relative frequency of exeedances. The hydrologist then works with these values under the assumption that the relative frequencies closely approximate the real probability.

Corresponding to probability (relative frequency) is the concept of the return period, which is the reciprocal of the probability. If, for example, the probability of an exceedance is 4 per cent (0.04), it is then said that such an exceedance has a return period of 25 years. The concept of the return period is sometimes misunderstood. It represents the average interval between two exceedances taken over a long period; it does not mean that if, say, the return period is chosen as 100 years, there will be exactly one exceedance within the next 100 years. In fact the probability that it will occur exactly once in the coming 100 years can be calculated and is some 37 per cent; the probability that it will not occur during that period is almost the same.

In the design of water resources projects the selection of a certain return period is important because it largely determines the dimensions of engineering structures and, consequently, their cost and service efficiency.Corresponding with this design return period is a certain magnitude of runoff known as the design runoff. The very concept of a design runoff implies that 'failure' will result with the occurrence of a larger flood or drought than that projected, and the probability that this will happen is always present. So in all projects based on a design runoff, a certain risk is involved. According to PILGRIM and CORDERY (1974) the design accepts that failures will occur, but that the resulting damage is both socially acceptable and will cost less than the construction of works with larger design runoffs and lower risks; in fact this is a trade-off with all the commensuration problems it brings with it.

Because in water resources projects the economic evaluation is based on the expected life of the project, it is not correct to take the return period as a direct design criterion. It is possible, however, to calculate the design return period

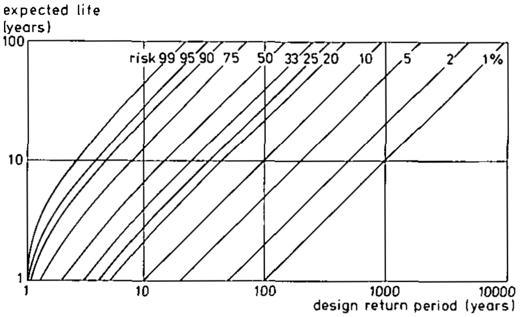


Figure 1.
Design return period as function of expected life of the project for various risk levels (adapted from BEN CHIE YEN 1970).

from the permissible risk of failure and the expected project life.
Figure 1 shows that if, for instance, a one per cent risk of failure is permissible in a period of 100 years, the design return period must be chosen as some 10,000 years.
Whether the design return period is chosen directly, or indirectly via the permissible risk of failure, the fact remains that the assessment of the runoff corresponding with this return period is the crucial factor. One of the most common problems the hydrologist faces is having to estimate a flood or drought either from a record of streamflow data that is shorter than the design return period or even without any streamflow data at all.

Developments in methods and models

A mathematical model can be defined as a simplified representation of a complex system in which the behaviour of the system is represented by a set of equations expressing relations between the different parameters; in this respect a formula can also be regarded as a mathematical model. In surface water hydrology, the system being represented in the model is the land phase of the hydrological cycle (Figure 2).
Historically, the science of hydrology started in the nineteenth century with the development of empirical methods. At the beginning of the pres-

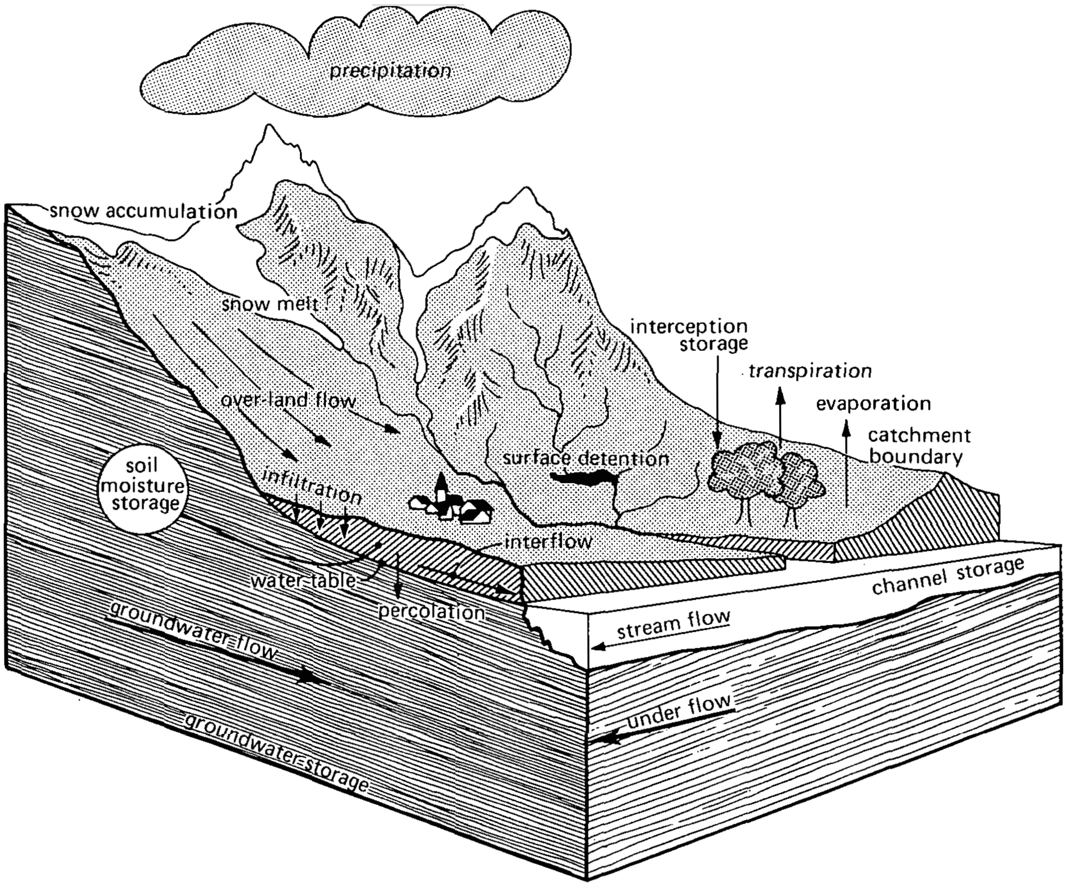


Figure 2.
The land phase of the hydrological cycle (adapted from FLEMING 1979).

ent century, it received an impetus with the introduction of probabilistic methods. Then, in the early 1930's, because rainfall records are generally longer and more numerous than streamflow records, theoretical hydrologists shifted their attention to deterministic (rainfall-runoff) methods, which in their turn led to the development of what are known as component models.

That was roughly the state of the art in the late 1950's, when the advent of the digital computer brought a powerful tool to the hydrologist and radically changed the application of mathematical models in surface water hydrology. With its very high rate of arithmetic computation, the computer made it possible to represent time and space variables and to integrate the different processes (components) of the hydrological cycle. Within the deterministic approach, the computer created a new tier – the conceptual model – which is sometimes referred to as a deterministic simulation approach. Introduced into the statistical approach, the computer led to the development of the stochastic model.

Most quantitative hydrologic methods can be classified either as deterministic or as statistical. Deterministic methods treat the hydrological processes in a physical way and make use of historical streamflow data as well as data on rainfall and other phenomena (infiltration, evapotranspiration, etc.) which affect the properties of runoff. These methods are called deterministic because, once the parameters are determined, deterministic methods always produce the same output from a given input. Statistical methods utilize information from the analysis of historical streamflow data only. Because these methods deal directly with streamflow its characteristics can only be described by the theory of statistics.

Among the many classifications that have been made of the available methods is that by FLEMING (1975). As shown in Figure 3, the Fleming classification, which will be used in this article, subdivides deterministic hydrology into empirical methods and conceptual models, and statistical hydrology into probabilistic methods and stochastic models.

Empirical methods

One of the earliest flood formulas was that devised by Mulvaney in 1851. Today, almost 130 years later, his rational formula is still famous and is still widely used as a method in design. Mulvaney's was the first formula to relate peak flow to rainfall intensity and drainage area. It was followed by a broad class of other empirical methods relating peak flow to similar and other physical characteristics of a drainage basin. VEN TE CHOW (1962) reviewed a number of these methods.

As the era of simple empiricism ended, that of 'modern' hydrology started in the early 1930's, with the work of SHERMAN (1932). Sherman's paper 'Streamflow from rainfall by the unit-graph method' represented a milestone in hydrology. It led to the development of component models, in which the land phase of the hydrologic cycle is broken into components, the major ones being rainfall, infiltration, evapotranspiration, aquifer response, and streamflow routing.

The essence of the unit hydrograph concept

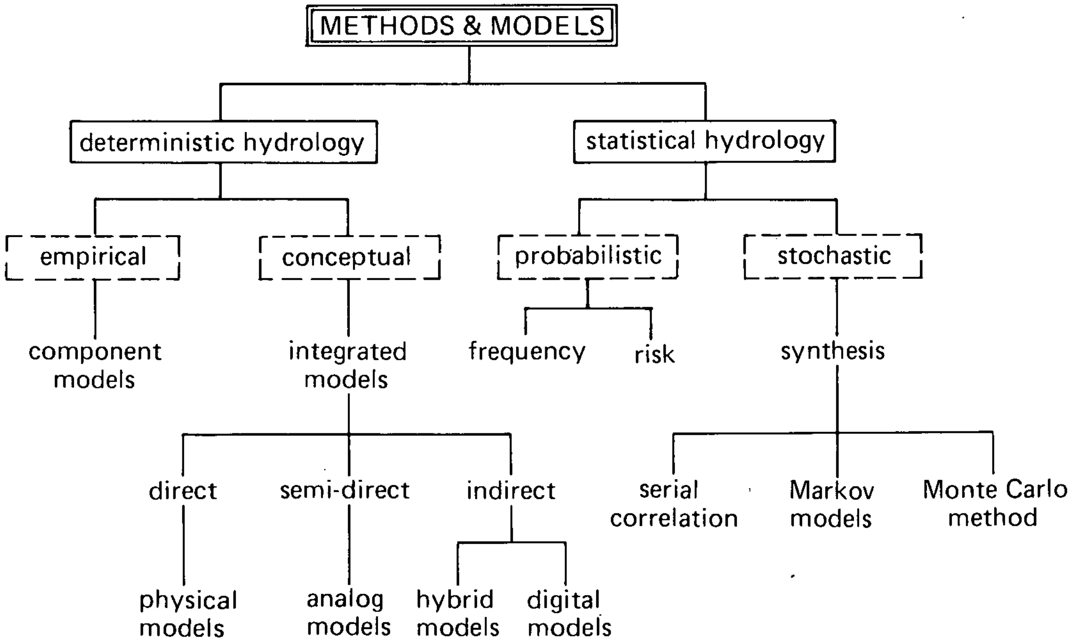


Figure 3.
Methods and models in surface water hydrology (adapted from FLEMING 1975).

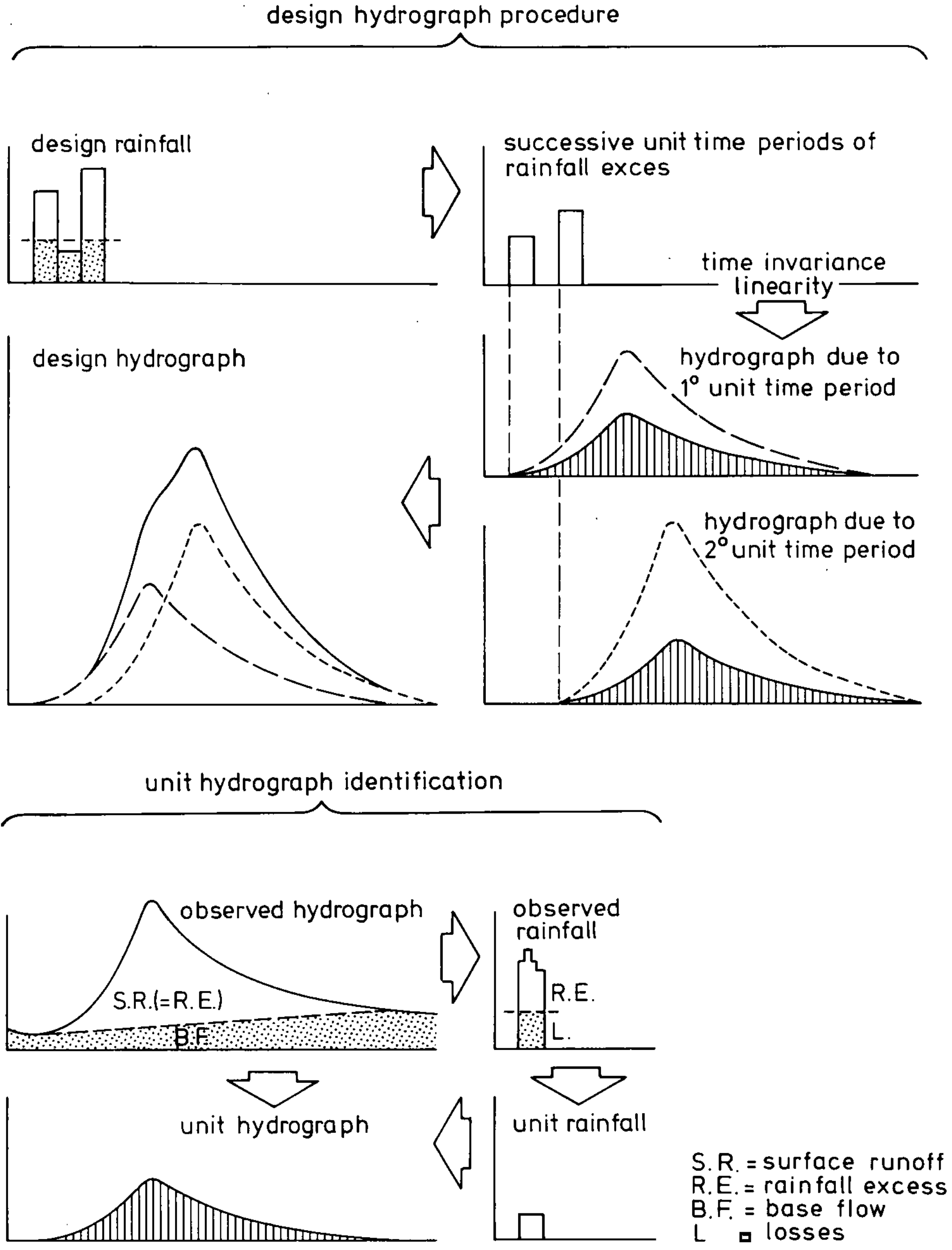
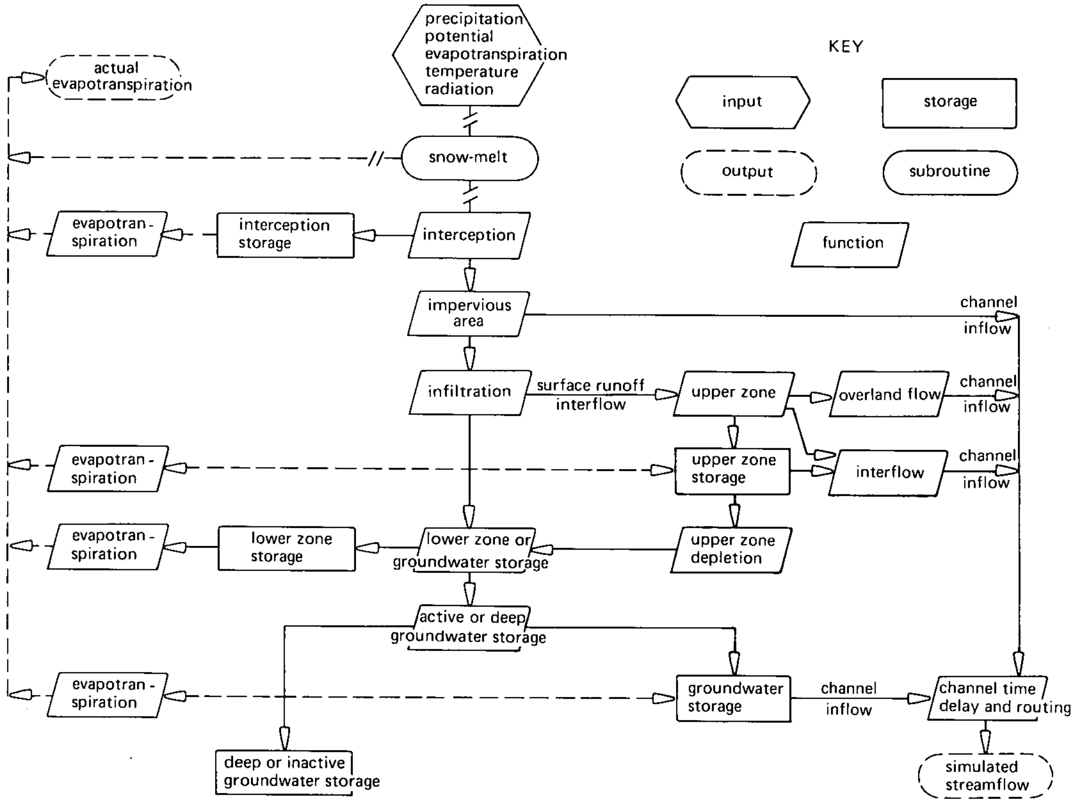


Figure 4.
Flow chart of unit hydrograph procedure.

(graph showing discharge with respect to time) is that since the physical characteristics of a drainage basin (shape, size, slope, etc.) are constant, one can expect considerable similarity in the shape of hydrographs resulting from storms of similar characteristics. Because the variable characteristics of storm rainfall cause variations in the shape of the resulting hydrographs, Sherman based his theory on a specified period of time, the unit storm period which gave the method its name. For this period he postulated that for every drainage basin a unique hydrograph existed, defining the complexities of the basin characteristics by a single empirical curve. the unit hydrograph. Figure 4 shows the basic operations involved in the unit hydrograph procedure.

In short, the observed hydrograph is separated into two parts: base flow and storm runoff. The storm runoff is assumed to be caused by the 'rainfall excess', so the observed rainfall is adjusted in the sense that the volume of rainfall excess equals the volume of storm runoff; the other part is regarded as losses due to interception, evapotranspiration, and infiltration. The actual amount of rainfall excess is reduced to 1 mm depth of rainfall excess and the corresponding hydrograph of storm runoff is drawn, being the unit hydrograph for that basin. Once the unit hydrograph has been identified a design rainfall is selected from the available rainfall records, the amount of the rainfall excess is then determined, and, by

Figure 5.
Flow diagram of the Stanford Watershed model (FLEMING 1975).



treating this amount of rainfall excess as a consecutive number of unit storm periods with different intensities and applying the principle of superposition, the design peak discharge is found. The concept of the unit hydrograph has been the subject of many papers; for more information reference is made to LINSLEY (1967) and DOOGE (1973), who reviewed the literature on the subject.

In the 1950's and 1960's the main emphasis in the use of component models was directed towards the problem of identifying unit hydrographs. Classical methods of unit hydrograph derivation were based first on trial and error and secondly on special methods such as the iterative procedure (COLLINS 1939). Modern methods can be classified either as transform methods or as correlation methods. In transform methods computer analysis of hydrographs was attempted on a large scale: NASH (1959) fitted hydrograph shapes to standard probability distributions by multiple regression; O' DONNEL (1960) attempted a similar approach using Fourrier series. In the correlation methods the least squares approach is the basis of the derivation of unit hydrographs. Both SNYDER (1955) and BODY (1959) expressed the necessary computations in matrix form and developed a program for the digital computer.

Both the empirical methods and the unit hydrograph concept are still extensively used; they have in common that only design flood volumes and design peak discharges can be estimated. For low flow estimates only one method exists, it is based on the theory of groundwater depletion.

Conceptual models

Whereas the component model approach uses discrete time periods, namely only periods of high flows, the conceptual model approach is an integration of the component theories on a continuous time basis, ranging from low to peak discharges. It seeks to simulate catchment behaviour by postulating a certain mathematical operation for each major component of the land phase of the hydrological cycle and linking the components together so that the appropriate interactions can occur. Because the form of these models depends upon the model-builder's physical concepts of the hydrological cycle, they are also known as conceptual models. In fact, there is no limit to the number of conceptual models that can be devised. The techniques of simulation include:

- direct simulation using physical models
- semi-direct simulation using analog models
- indirect simulation using hybrid and digital models

The disadvantage of the first two techniques is that for each drainage basin an entirely new model has to be determined, whereas by indirect simulation the model can be applied to a great number of drainage basins, only the parameters of the model needing adjustment.

One of the first to realize the possibilities of the digital computer in rainfall-runoff modelling was R. K. Linsley, who developed the Stanford Watershed model (CRAWFORD and LINSLEY 1966). This model is based on a moisture accounting procedure. Figure 5 shows a flow diagram of the model. The principal input data are hourly precipitation and daily potential evapotranspiration.

The model outputs hourly streamflow any time the flow is above a preselected base level, mean daily flow, total annual runoff, end-of-the month soil moisture and groundwater storage, actual evapotranspiration, etc. When a drainage basin receives snow, the model contains a routine which keeps an account of the snow on the ground and calculates the melt rates. The water melted from the snow is fed into the model as precipitation. Depending upon the exact configuration used, this model has between 20 and 30 parameter values, all of which have to be evaluated numerically in fitting the model to any given basin. The Stanford Watershed model was followed by a great number of deterministic, digital simulation models. Two groups of conceptual models can be distinguished:

- General purpose models based on a comprehensive structure of the hydrological cycle and representing a broad variety of regimes.
- Special purpose models developed for specific problems, such as reservoir regulation, flood and drought forecasting, design drainage systems, agricultural engineering, etc. CEMBROWICZ et al. (1978) and FLEMING (1979) have discussed and compared a number of these models and have indicated which models can be used for certain specific problems.

When conceptual models are used in the quantitative assessments of extremes, the procedure is as follows: recorded rainfall data and other physical characteristics of a particular basin are fed into the model; from these input data the model simulates the corresponding runoff data which are then compared with the observed historic ones. In the next step the input parameters are adjusted in the sense that the simulated runoff data fit as closely as possible the historic ones; this process is also called the calibration. Figure 6 shows an example after calibration. When long records of historic rainfall data exist, these records can be used as input data and the model then outputs the corresponding simulated record of discharges. Another possibility is that based on the statistical characteristics of the historic rainfall data, rainfall intensities being simulated stochastically. These stochastic rainfall data are then fed into the deterministic conceptual model, yielding long hypothetical sequences of discharges. OTT (1971), for example, used a version of the Stanford Watershed Model and an hourly rainfall model to synthesize a 500 year record of runoff. In both cases these long simulated records can be used to assess the design runoff.

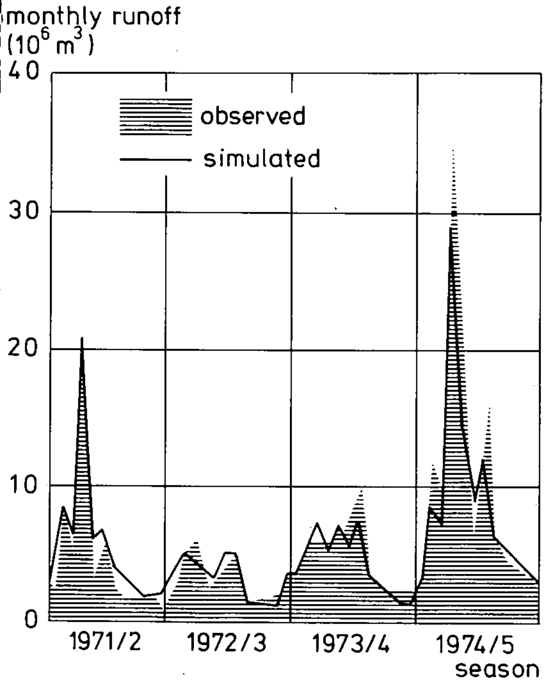


Figure 6.
Simulated runoff after calibration.

It is generally agreed among hydrologists that conceptual models are powerful tools in the analysis of the different streamflow characteristics. Such models have been applied to many drainage basins throughout the world and the accuracy of the results has been generally good, limited primarily by the quality of the input data.

Probabilistic methods

Since the pioneering work of FULLER (1914) who analyzed a series of floods and estimated the flood magnitude for any specified probability,

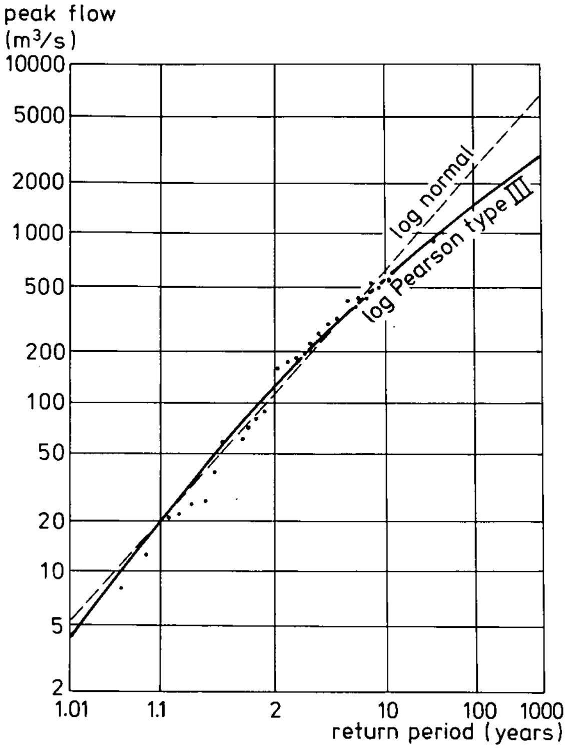


Figure 7.
Fitting of two distributions to the annual maxima of the river Styx (PILGRIM and CORDERY 1974).

countless papers on the application of probabilistic methods in hydrology have been published. The simplifying assumption made in the probabilistic approach is that the occurrence of an event is assumed to follow a fixed probability distribution. A probability distribution expresses the relationship between the magnitude of an event and the probability of this magnitude being exceeded. In probabilistic methods the available data on streamflow are used to fit a certain frequency distribution, which in turn, in the case of extreme events, is used to extrapolate from the recorded discharges the discharge with the design frequency. Difficulties in probabilistic methods arise from two major sources:

- the true form of the frequency distribution is not known
- sampling errors

Numerous different frequency distributions have been used in hydrology, but it is not known to which distribution the discharges can be best fitted. Historical records are much too short to afford any definite empirical evidence. This problem is aggravated by the fact that runoff data can often be fitted with satisfactory accuracy to several types of distributions (Figure 7). Goodness of fit tests generally show no significant differences in the fit of the data to the different distributions. However, the tails of the distributions can sometimes be very dissimilar, and these are the probability regions of interest to the designer. Table 2 illustrates the differences in flood discharges of various frequencies estimated from the two distributions.

There is no general agreement among hydrologists as to which of the various available theoretical distributions should be used. For example, SPENCE (1973) compared the fit of the normal, 2-parameter lognormal, type I extremal, and log type I extremal distribution to annual maximum flows and found that the lognormal was the best fitting. CRUFF and RANTZ (1965) compared six frequency distributions and found the Pearson type III distribution to be the best, whereas BENSON (1962), in a study of 100 longterm flood records, found that no one type of frequency distributions gave consistently better results than the others. JOSEPH (1970) studied the probability distribution of annual droughts on 37 stations in the Missouri River basin, U.S.A. Using five distributions, viz. normal, lognormal, square root normal, Weibull and gamma-2 distributions, he arrived at the conclusion that gamma-2 distribution was acceptable for 35 of the 37 stations. In contrast the minimum discharges of the Mekong River at Vientiane, Laos, were evidently lognormally distributed (MOORE and CLABORN 1971). In short, not a single distribution is acceptable to all hydrologists.

Sampling errors, the second major source of difficulty in frequency analysis, relate to estimating the best values of the population parameters once the type of distribution has been selected.

Table 2.
Flood of various frequencies estimated from Figure 5 (PILGRIM and CORDERY 1974).

Frequency distribution	Period of record	Years	Estimated flood (m^3/s)	
			100 yr	1000 yr
Log normal	1939–66	28	2,400	6,200
Log Pearson Type III	1939–66	28	1,500	3,000

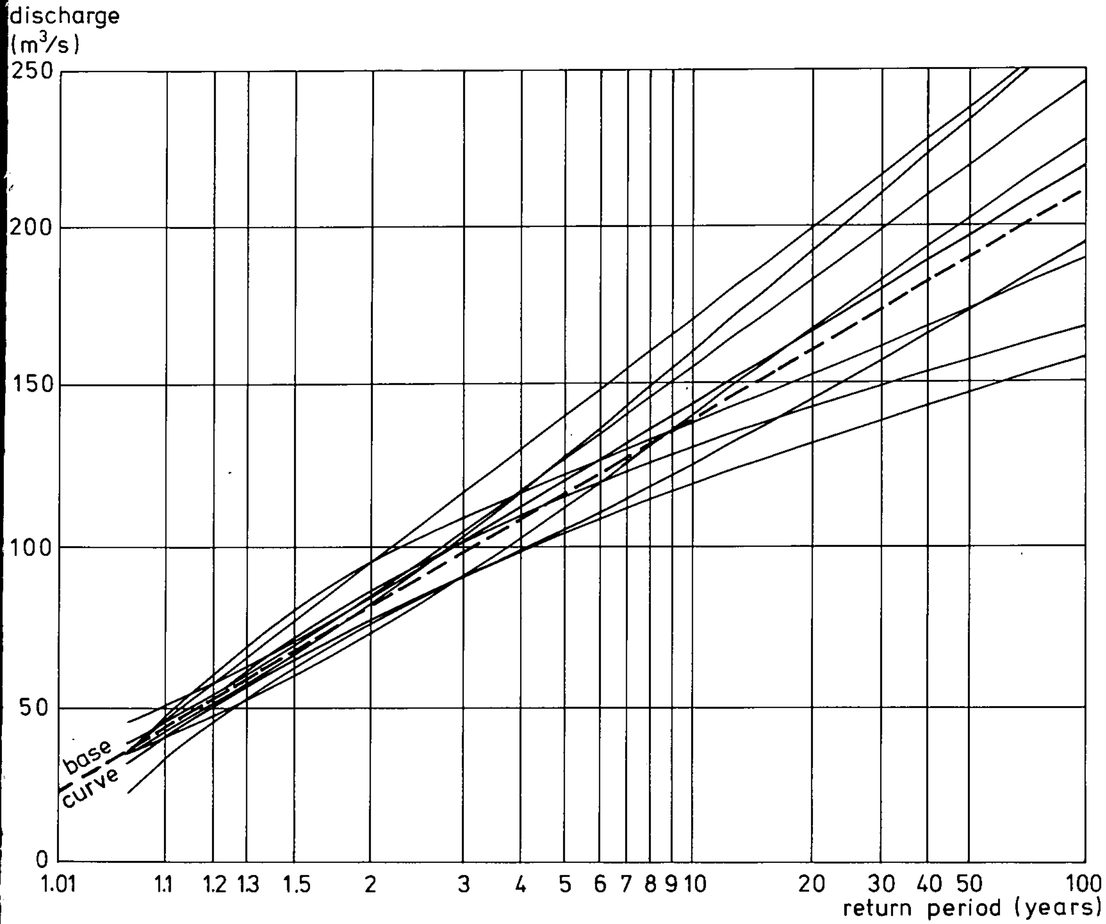


Figure 8.
Frequency curves for 50-year periods (adapted from BENSON 1960).

The magnitude of sampling errors is illustrated by the numerical sampling experiments reported by BENSON (1960). A population of 1000 values fitting a selected frequency distribution was randomly divided into samples of various length. Figure 8 reproduces some of the resulting frequency curves of the twenty 50-year samples. Even with a length of 50 years, these results show that large errors are possible and that the frequency curve of recorded floods may be quite different from the true curve of the population.

NASH and AMOROCHO (1966) conclude, however, that errors due to sampling variance only coverge towards fixed proportions of the estimates for high return periods. They maintain that, if one could be certain that the assumed form of the probability distribution was correct, magnitudes corresponding to even the very highest return periods could be estimated with quite tolerable accuracy from even relatively small samples

Stochastic models

Many hydrological sequences exhibit a departure from randomness in that large values tend to be followed by large ones, and small values by small ones, so that runoff values of similar magnitudes tend to persist throughout the sequence. If we are interested in monthly or daily flows, we find that the flow in a particular month or on a particular day will be influenced by the flow(s) of the previous month(s) or day(s), whereas the magnitude of extremes is seldom influenced by the occurrence of previous extremes (from year to year). Where persistence is present, probabilistic methods cannot be used in planning and designing water resources projects.
Stochastic modelling is a relative newcomer to the science of hydrology. Some of the concepts of stochastic simulation had been used much earlier, in reservoir design, but widespread application did not begin until the 1960's. The approach in stochastic modelling is to generate long hypothetical sequences of discharges based on the statistical and probability characteristics of the historic records; this approach is also called stochastic simulation, and is comparable to deterministic simulation with conceptual models.
As an example, reference is made to a study by O'DONNELL et al. (1972) who analyzed the flood magnitude-frequency relationship for the river Vardar, Jugoslavia. Using the 42 annual max-

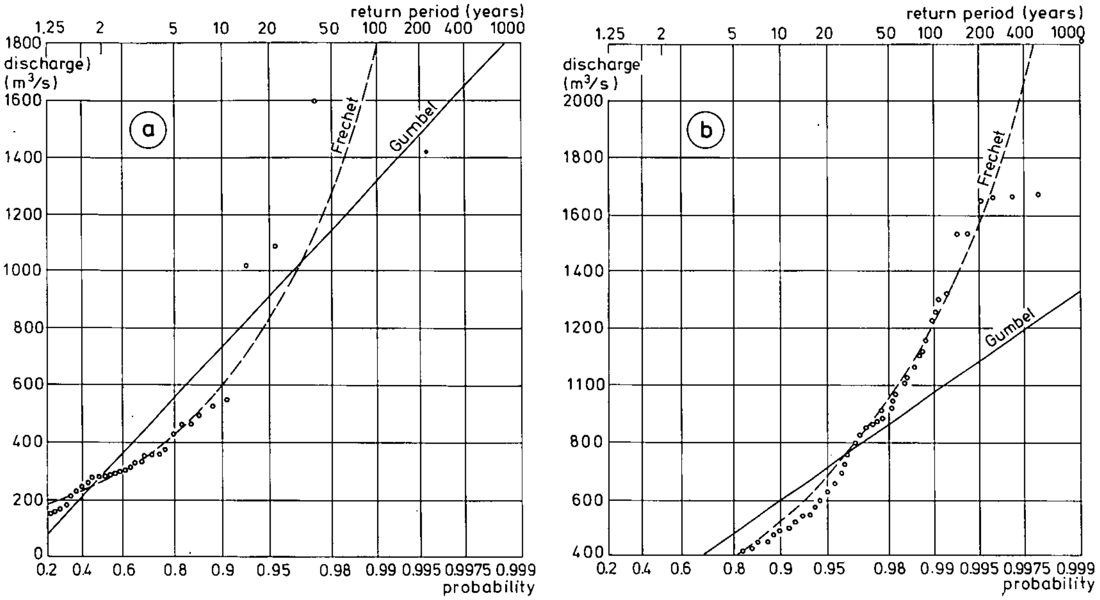


Figure 9.
Generation of daily data.

imum floods, they fitted these events to Gumbel and Fréchet distributions. For the largest annual event in the 42 years of record (1600 m³/s), widely different return periods of 80 years (Fréchet) and 300 years (Gumbel) were found (Figure 9a).

They then felt that stochastic simulation would improve the results, because in probabilistic methods only a fraction of the information contained in the 42 years of records is used, i.e. one item of data per year. A total of 25 sets of daily data, each set 42 years long, were generated and the annual maximum floods abstracted. Figure 9b shows the generated annual maxima (in excess of 400 m³/s) fitted to the two distributions. It was concluded that the Fréchet distribution adequately represents the flood magnitude-frequency relationship for the river Vardar and that the historic flood of 1600 m³/s has a return period of just over 200 years.

The procedure in stochastic modelling consists of two parts:

- the choice of a proper model for generating flows
- the choice of a proper probability distribution for the input.

The models used are basically of the Markov or the Monte Carlo type.

The difference between the two lies in the treatment of the data. The Monte Carlo method considers the data to be totally independent and is concerned with defining the probability distribution from the historic data population and, then using a selected random generating technique to produce the synthetic series of data.

The Markov technique is concerned with non-pure random data, i.e. data composed of both causal and random elements. In the Markov lag-one model, for instance, which means that the flow in, say, a particular month is only influenced by the flow in the previous month, the flow is assumed to be the sum of:

- the mean flow in that month
- a proportion (given by the correlation coefficient) of the departure of the previous flow from its mean
- a random component (residual)

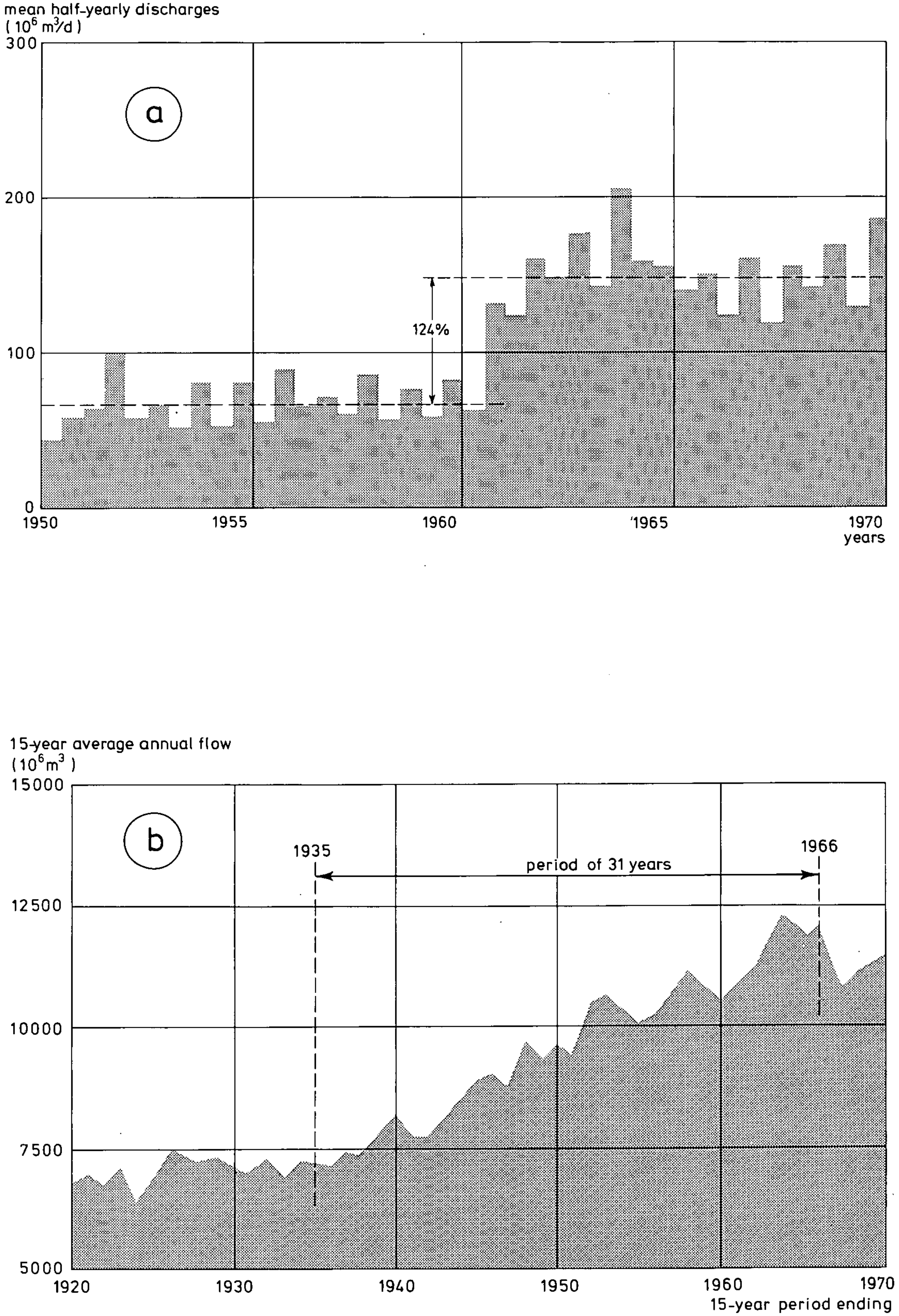
The first two components are the statistical part, directly derived from the data, and the third is the stochastic element which is commonly assumed to be either normally, log-normally, or gamma distributed.

Markov models were the first stochastic models applied for the generation of streamflow sequences (THOMAS and FIERING 1962; YEVJEVICH 1963); these models are short-memory models. Since then, there has been an almost explosive growth in the development of models for the generation of synthetic hydrological data sequences.

The assumptions implicit in the Markov type models, however, have been challenged (MANDELBROT and WALLIS 1968). The consideration of short-term and long-term dependence has led hydrologists and statisticians to propose various alternative models for the stochastic simulation of hydrologic time series. To preserve very long-term cycles in the streamflow process, the fractional Gaussian noise (FGN) model was developed (MANDELBROT and van NES 1968), and to describe a wide range of behaviour in time series BOX and JENKINS (1970) developed an Autoregressive-integrating-moving average (ARIMA) model.

Stochastic simulation can be applied to both

Figure 10.
Changes in hydrologic systems.



flood and drought phenomena.
ASKEW et al. (1971) concluded from a comparative study that for simulating periods of low flows the time series is more closely approximated by FGN-models than by Markov models. SALAS and BOES (1979) also question Markov models for their limitations to reproduce droughts.
In any case, the published literature is formidable, but because of the strong statistical and mathematical background much of its significance is lost to the hydrologist in the field.

Conclusions

As will be clear by now, the hydrologist has a very great number of methods at his disposal. Far from being an advantage, however, this great number is confusing because not one single method can be proved to be absolutely correct; they are all different approximations of the very complicated system that nature is. The confusion is aggravated by the arguments going on among theoretical hydrologists about different types of methods, not only about the different concepts within a certain type of method, but also about the main subdivision, of deterministic and statistical methods. It is not the object of this article to go further into this matter, but in regard to the antithesis between deterministic and statistical methods it is worth mentioning that QUIMPO (1971) and DOOGE (1972) pointed out that

Markov and ARIMA models respectively – both stochastic models – are in principle equivalent to certain types of conceptual models.

Although the deterministic and statistical methods have certain basic differences they share two characteristics of primary importance: their dependence on historical records for the values of the parameters and the assumption of time-invariance of the hydrologic systems.

The first characteristic means that the results of both these methods are affected by the correctness of the historical records. In many instances the records are too short to represent the true distribution of the variables in statistical terms: the historical data record is not a correct sample of the universe of natural events.

The second characteristic requires that hydrologic systems must not change in time, relative to their behaviour during the recorded past. In reality hydrologic systems change often, either through natural or artifical causes. As an illustration Figure 10a shows a positive jump of 124 per cent in the mean monthly discharges of the river Nile, while Figure 10b shows an increase in the 15-year average annual flow of the river Kafue of some 66 per cent.

The above considerations have perhaps only aggravated the bewilderment that the hydrologist is facing nowadays. FELDMAN (1979) concluded that empirical and probabilistic methods may be good for small areas where river routing and storage effects are not significant, but that for larger areas and studies the simulation model is the best tool. There are two main alternatives of flow simulation:

- stochastic simulation (without consideration of precipitation)
- deterministic simulation, starting from simulated precipitation

Stochastic simulation can be used if sufficiently long time-series of flow observations are available. In all other cases deterministic simulation must be applied.

The fact remains that different methods are available for different purposes. It is therefore of the utmost importance that unbiased criteria and standardization are made available to test all the proposed models and to identify their individual merits and advantages for specific applications.

CEMBROWICZ et al. (1978) analyzed 23 mathematical models dealing with hydrological variables, both deterministic and stochastic. Some of their findings were:

- Some of the models, well-known all over the world, were certainly not the best for a particular purpose.
- Other models, which are not so well-known, turned out to be most satisfactory for that purpose.
- Some models revealed a very sophisticated structure requiring detailed input information (up to 166 parameters) which is seldom available. Therefore, less complex models are often more suitable for practical purposes.

The last view is endorsed by the World Meteorological Organization (WMO) which published a report in 1975 on the intercomparison of rainfall-runoff models, stating that under certain conditions simple models are as effective as the more elaborate ones. The WMO report also indicated the need to develop objective criteria which can be used to compare the performance of the different, existing, models.

In summary, it can be stated that the field of hydrological modelling has undergone extensive development, stimulated by the introduction of the digital computer, without which conceptual modelling techniques and stochastic generations of streamflow data would be unthinkable.

The fact remains that the gap between theoretical and applied hydrology is still open.

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Developments in planning of irrigation projects

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Importance of irrigation

It has long been known that by regulating the water supply in agriculture, crop production can be substantially increased. The rise and decline of such ancient civilizations as existed in Egypt and Mesopotamia and in the Indus and Yellow River Valleys were closely related to the state of irrigated agriculture.

With the rapid growth of the world's population in the past century and the consequent increasing demand for agricultural products, the vital role of irrigation is once again being recognized. Its importance in the developing countries is illustrated in Table 1 (Page 100).

The role played by irrigation depends primarily on the climate. In arid regions, no substantial crop yields would be possible without it. In semi-arid regions, where rainfall may be poorly distributed over the year, irrigation can bridge drought periods and ensure a more stable and reliable production. In the humid tropics, especially in densely populated regions where the need exists for higher yields per unit of land, irrigation can permit a second crop to be grown. Moreover, if practised under well-controlled water management, it enables the optimization of other agricultural inputs such as fertilizers and high-yielding varieties. This is illustrated for rice in Figure 1.

The irrigated area

During the last decades, the area under irrigation has undergone a stupendous expansion, as can be seen in Table 2. Around 1900, only some 50 million ha was irrigated. According to the table, this figure has now increased to almost 200 million ha, which represents 1.5 per cent of the world's total land area and about 14 per cent of its total cultivated area. As can be seen from the table, a large proportion of the irrigated area is located in the developing countries. Of the 50 million ha irrigated in the richer countries, the U.S.A. and U.S.S.R. together account for 33 million ha. FAO's world total area of 198 million ha differs considerably from the generally quoted 223 million ha. The latter figure originates from ZONN (1974). A comparison of the detailed figures from both sources reveals that the difference is mainly due to different data for a few countries: China (76.5 million in ZONN vs. 48.7 million in FAO), U.S.A. (21.5 vs. 17.2 million), and India (39.0 vs. 35.2 million). Detailed discussions on irrigation per country are given by FRAMJI and MAHAJAN (1969) and by FUKUDA (1977). When we compare the figures from these sources for certain projects with the real figures as we know them from personal experience, it is obvious that the official figures deviate significantly from reality. The official figures often give the planned irrigable or cultivable area, whereas the

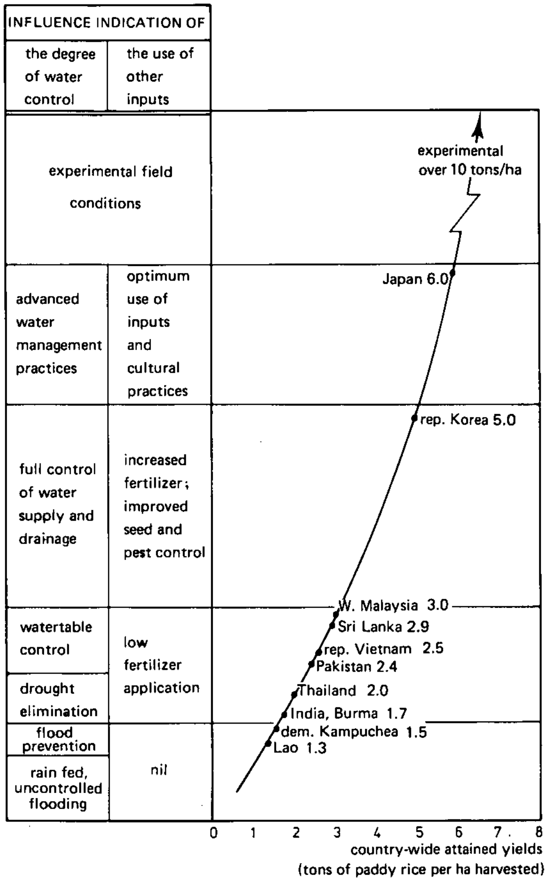


Figure 1.
Influence of water control, improved management, and additional inputs on yields of paddy rice (FAO 1979a).

Table 1.
Importance of irrigation according to regions (1961–1963) (FAO 1970)

Region	Irrigated area			Value of crop production from irrigated land as percentage of total
	In million ha	as percentage of Arable area	Harvested area	
Africa South of the Sahara	1	0.7	1.7	3
Asia and Far East	44	20.9	23.5	40
Latin America	11	8.1	11.5	17[1]
Near East and N.W. Africa	17	23.9	32.9	68
Total or average	73	12.9	18.6	34[1]

[1] excluding Central America.

Table 2.
Increase in irrigated area 1955–1977 (based on data from GULHATI 1955 and FAO 1979b).

	1955		1977		Increase	
	million ha	% of world total	million ha	% of world total	million ha	%
Developed countries	28	23	53	27	25	89
China	31	26	49	25	18	58
Developing countries	62	51	96	48	34	55
India	(24)		(35)		(9)	
Pakistan	(9)		(14)		(5)	
World total	121	100	198	100	77	64

area actually equipped for irrigation is much less. Sometimes only a part of the equipped area is actually irrigated. A world-wide ICID survey (BOS and NUGTEREN 1974) covering about 4 million ha revealed a difference of 40 per cent on the average between equipped and (net) irrigated area, although the equipped or even the planned irrigable area was officially given as the actually irrigated area. Futhermore, some countries included the irregular sprinkling of pastures and occasional uncontrolled flooding as part of their 'irrigated area'. For the above reasons, it seems likely that the present 198 million ha estimate is still on the high side.

The prognoses of 270 million ha for 1990 (FAO 1977) is said to represent an attempt at a realistic estimate, taking into account, as it does, possibilities and constraints encountered in the various countries in the physical, technical, financial and organizational senses. The potential irrigable area in the world has been estimated at 450–500 million ha (MOEN and BEEK 1974). For further re-

Surface irrigation will remain a widely used application method.

flections on this subject see the article of Schulze and van Staveren.

Field application methods

One of the most discussed developments in irrigation technology in the last decades has been the introduction of sprinkler and drip irrigation. Sprinkler (or overhead) irrigation is the application of water, under pressure, through the air in the form of spray. It was developed at the beginning of the century, but only after aluminium became available at reasonable prices in the 1950's was it used on any wide scale. Drip (or trickle) irrigation is the frequent application of small doses of water (1 to 5 l.h^{-1}) locally to the plant. Water is applied under low pressure through orifices (emitters) in plastic tubes. The basic system was already known in glasshouse culture, but was not applied in agriculture until the early 1960's.

In literature and at congresses and seminars, sprinkler and drip irrigation have been receiving enormous attention. We estimate that for every 35 ha under drip irrigation, one article has been written. (This ratio applied to surface irrigation would yield about 5 million articles!). This attention seems out of all proportion to the area actually served by drip irrigation. At present the total area under drip is only about 100,000 ha and, because of its limits of application, we do not expect that this area is likely to increase dramatically in the future. The area served by sprinkler is estimated to be less than 15 million ha, of which 10 million ha are in the U.S.A. and U.S.S.R. together.

So, in spite of all the efforts to promote these modern techniques, their role in the developing countries, where so much of the world's irrigation is practised, is almost negligible. Why then have they been receiving so much attention? And what are their real prospects for the future? (Before discussing these questions, we must first observe that neither sprinkler nor drip irrigation is suitable for some crops; rice, which occupies about 25 per cent of the total irrigated area, is a pertinent example).

The two main incentives for developing sprinkler and drip irrigation were to save on labour requirements and to reduce water use. These two items are usually mentioned as being the most important advantages of these methods.

Let us first discuss the labour requirements. Precise data on this subject are scarce in literature. The figures presented in Table 3 are based on scattered data and on the authors' own judgements. As the table shows, considerable savings in labour can indeed be attained by most of the sprinkler and drip methods. As also shown, however, there is a general tendency for these savings to be accompanied by higher investment costs. In most of the developing countries, the situation is not particularly calling for labour-saving but expensive techniques (FAO 1976).

With the higher investment costs for sprinkler, and especially for drip irrigation, the fixed annual costs will also be higher, the more so because the depreciation period is normally shorter than for surface irrigation facilities. In the annual operating costs, the energy consumption constitutes a vital element. The importance of energy consumption, even apart from the presently rising energy costs, is well illustrated by BATTY et al. (1975)

Table 3.
Labour requirements and investment costs for various field irrigation systems.

Irrigation method		Labour requirements man-hour per irrigation per ha	Capital costs of field system US $/ha
surface	furrow	1–3	100–400
	border	0.5–1.5	100–400
	basin	0.1–1	100–400
sprinkler	hand-moved laterals	1–2.5	400– 800
	tractor-moved laterals	0.5–1	600–1000
	self-moved systems	0.05–0.3	1000–1800
	permanent systems	0.05–0.2	1800–2200
drip	orchards	0.1–0.3	1200–1800
	row crops	0.1–0.3	1500–2500

and by CHEN et al. (1976). Figure 2a shows the annual pumping energy requirements, assuming the indicated application efficiencies (e_a). For low water lifts the energy consumption for drip and sprinkler is higher than for surface irrigation, even with great differences in efficiencies. In many cases these extra energy costs will outweigh any savings in labour.

This means that, besides the higher fixed annual costs for drip and sprinkler irrigation, also the annual operating costs will be higher (see also Table 4).

Figure 2b shows, from a somewhat broader view, the total annual energy requirements, including the energy used in manufacturing the materials, and in levelling, ditching, etc.

From the above considerations it will be clear that if drip and sprinkler irrigation are to have a future, their higher costs must be offset by greater benefits. An often heard claim is that these benefits accrue from a more efficient water use. But is that true? In considering this question, we shall divide it into two parts:

- field application efficiency, in the sense as defined by ICID (BOS 1978)
- yields per volume of water used by the crop.

On the subject of field application efficiency, we make the following observations:

- Much confusion exists in literature, mainly because of the use of different definitions of the term 'application efficiency' and, more seriously,

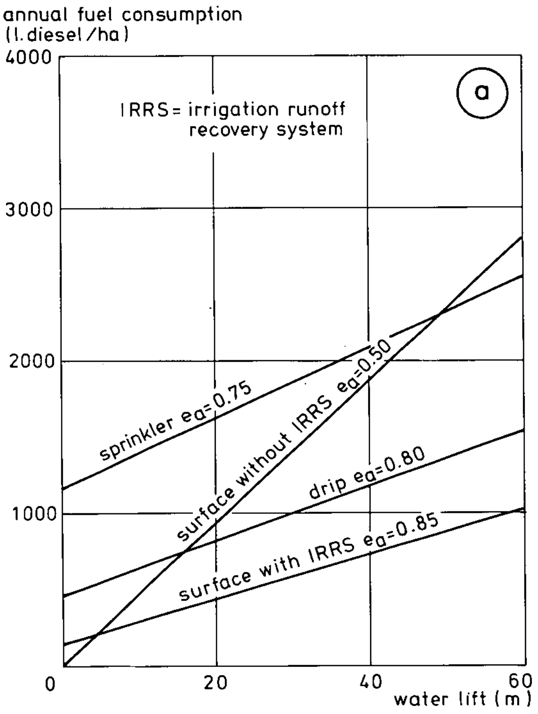


Figure 2a.
Average pumping energy required for surface, sprinkler, and drip irrigation systems with different water lifts (based on data from BATTY et al. 1975).

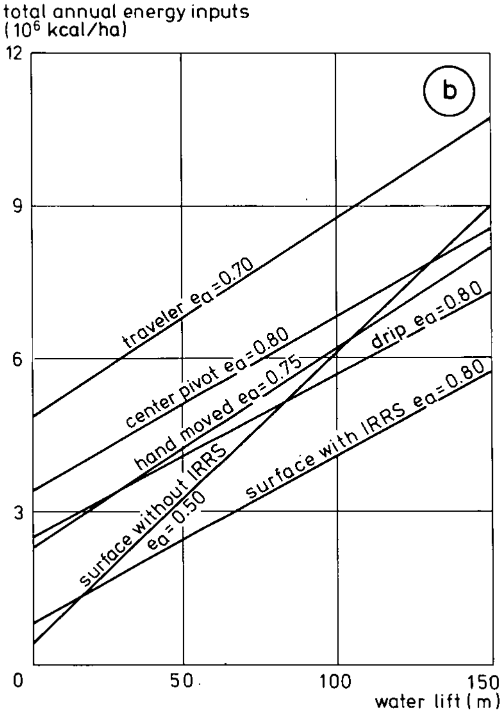


Figure 2b.
Total energy inputs per ha for six irrigation systems with different water lifts (adapted from BATTY et al. 1975).

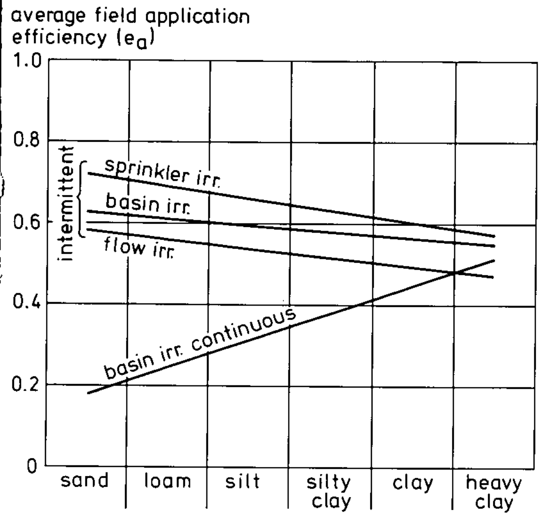


Figure 3.
Average field application efficiencies for various irrigation methods with reference to soil type (BOS and NUGTEREN 1974).

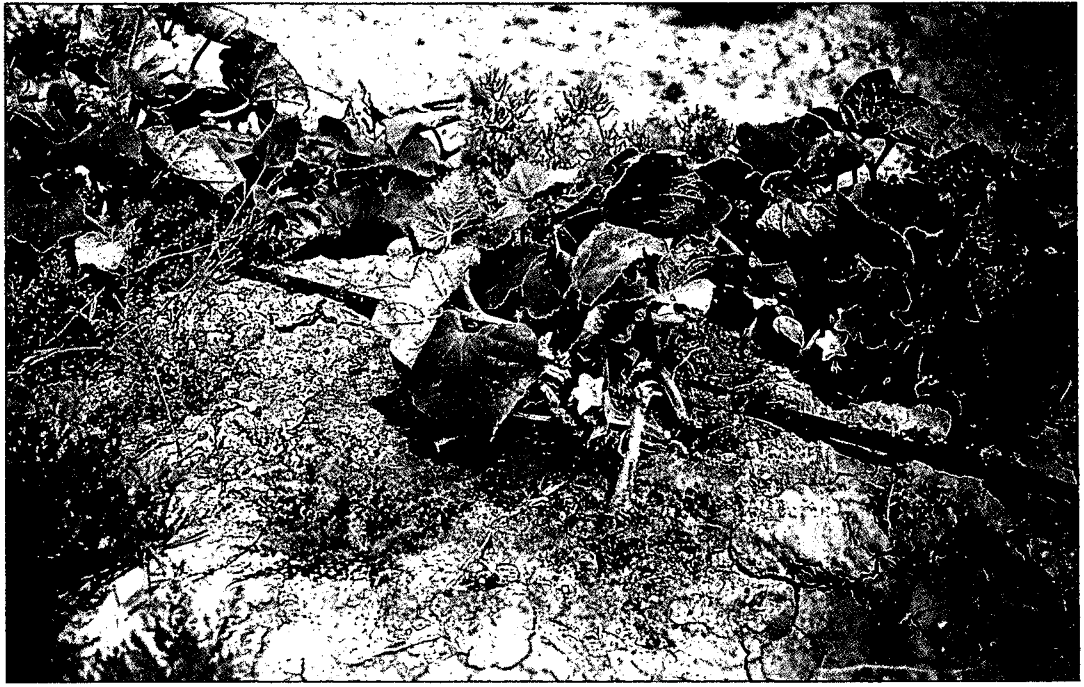
in many articles, because of the total lack of any precise definition.

- Figure 3, based on the 1974 ICID survey on efficiencies, shows that different efficiencies are found in practice. The reader will note, however, that the average efficiency for sprinkler does not reach the often claimed 0.80-0.85. Similar and higher figures (0.80-0.90) are also customarily claimed for drip irrigation, but have not been found on project scale. On the contrary, field reports regularly describe problems with clogging of the emitters, resulting in a poor uniformity and consequently in a low application efficiency and even low yields. It should also be noted that the figures for sprinkler are based mainly on data from the U.S.A. and Western Europe, whereas the figures for surface irrigation also include all the data from the developing countries. It could therefore well be that different management practices account for part of the differences in efficiencies.
- Several investigators have shown (e.g. KRUSE and HEERMAN 1977) that with a proper field layout and a proper handling of the irrigation water high application efficiencies can also be attained with surface irrigation.
- In line with the above considerations, the idea is more frequently being met in literature that the application efficiency depends less on the irrigation method as such and more on the design and operation.
- Another important aspect of operational practices, and one strongly influencing the actual application efficiency, is the question of when to irrigate and how much water to give. Modern, often computerized, irrigation scheduling services have been developed to answer these important questions (JENSEN 1978).

As for the supposedly higher yields obtained with drip or sprinkler irrigation, literature does not provide convincing evidence for sprinkler. For drip irrigation the problem is complicated. It is commonly stated that drip produces higher yields, but the actual results of investigations are confusing and contradictory. Some investigators find considerably higher yields with drip methods (e.g. SINGH and SINGH 1978); others (e.g. FREEMAN et al. 1976) none at all. Results may depend on specific conditions of soil, water, climate, and crops. JOBLING (1974) points out that in many cases drip is compared with sprinkler and surface methods 'under conditions of coarse soil and saline water where neither of the conventional methods had a chance to operate effectively'. Often, the yields obtained by the various methods are compared on the basis of the water supplied at the field inlet, not the water applied to the plant. Thus, in comparisons of yields per volume of water applied, elements of application efficiency are involved. A general trend seems to be that yield differences diminish, the more this efficiency aspect is eliminated from the comparison. Another point is that if high yields are obtained, this mostly appears to be on a small scale, under completely controlled conditions, so not representative of project conditions.

Of course, the above considerations are very general ones. Both sprinkler and drip irrigation can have certain advantages under certain conditions such as: specific crops (e.g. trees or vegetables for drip, high value crops), soils (light or shallow), water scarcity, labour scarcity, or irregular topography. However, on the whole it seems justifiable to quote HAINE (1977) who said: 'Better land smoothing and improved layouts have ensured that fields, which a year or two ago would, have been laid out to sprinkler irrigation at a cost of $ 1200 per ha, are now being laid out to furrow irrigation at a cost of $ 400 per ha with savings in pumping costs also. It remains to be seen whether the slight extra cost and lower yield forecast were correct, but return on capital will probably be some 2$\frac{1}{2}$ times higher for furrow than for sprinkler.'

All in all, there seems every reason to place emphasis on improvements in surface irrigation. Let us now look at some of the advances that have



Drip irrigation may lead to salinity problems if water is used 'too efficiently'.

been made with these methods (see also JENSEN 1978):

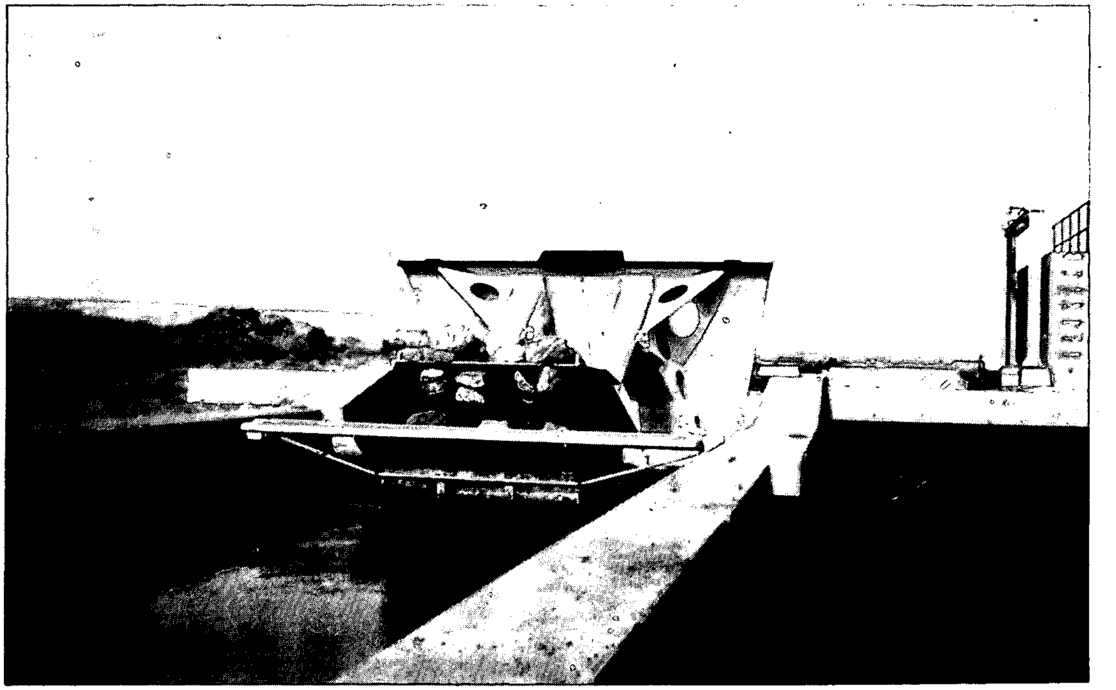
- The hydraulic design of the field can be improved. More insight has been gained into the cross-sections and lengths of furrows and borders in relation to the hydraulic gradient, infiltration rate, unit discharge, and water requirement (MERRIAM 1968, KAPOTODES and STRELKOFF 1977).
- Precise (laser beam controlled) levelling techniques enable the use of level basins on which high application efficiencies can be obtained with easy operation (DEDRICK et al. 1978).
- Seepage from the field ditches can be avoided by lining them or by using light-weight low-pressure pipes instead of a head ditch. Such pipes can be fixed or movable and have gates at the head of each furrow.
- The field runoff at the downstream end of a border or furrow can be collected and re-used, either by gravity discharge into a downstream canal or by pumping the water back into the same field or distribution canal (BONDURANT 1969, STRINGHAM and HAMAD 1975). Such re-use by additional pumping is also being applied in some rice areas, mostly to facilitate operations in time of peak water use.
- The application of water can be fully or partially automated. In the last decade, operational timers, valves, and remote-control equipment, have been developed for this purpose (HUMPHERYS 1978)

Table 4.
Estimated operating costs and total costs per hectare for irrigation with various systems in Nebraska (adapted from EISENHAUER and FISCHBACH 1977).

	Gated pipe without re-use	Gated pipe wit re-use	Automatic gated pipe with re-use	Center pivot
Water applied, cm/year	43	36	30	30
Water application efficiency	60	75	85	85
Operating pressure, bars	0.55	0.55	0.55	4.83
Fuel, $ 0.90/gallon[1]	$ 45.52	$ 40.97[2]	$ 35.12[2]	$ 71.81[2]
Oil, $ 5.45/gallon	5.04	4.14	3.58	7.96
Maintenance and repairs	8.00	8.46	9.73	13.00
Labor, $ 5.00/hour	12.76	12.76	6.18	6.18
Total operating costs/ha. year	$ 71.32	$ 66.33	$ 54.61	$ 98.95
Total fixed costs/ha. year	78.05	83.33	135.84	147.59
Total irrigation costs/ha. year	$ 149.37	$ 149.66	$ 190.45	$ 246.54

[1] Based on 30 m well lift and pumping plant operating at Nebraska Standard.
[2] Includes cost of pumping reuse at 5 cents/kw-hr.

The actual operation of a structure often differs from the planned one.



All these improvements in surface irrigation are to some extent the result of the wish to save on labour, but to a greater extent of the wish to increase application efficiencies at energy consumptions lower than for sprinkler systems. Table 4 compares some of the aspects of different irrigation methods. The practical application of these improvements is still very limited, but we expect that at least some of them will become widely used. Particularly appropriate for the developing countries are improved field layout, runoff re-use, and gated pipes.

Conveyance and distribution

In the design of the conveyance and distribution systems, whether by canal or conduit, hardly any development can be observed over the last decades. Construction techniques and equipment have changed, but systems are still designed as they were many decades ago. Perhaps nowadays, some designs are even less well balanced, because design teams seldom have as much time to spend on their assignments or have as much knowledge of local conditions as designers did in earlier days. Even so, the canal layout, the determination of canal capacities, and the hydraulic and structural design of canals and structures have not essentially changed.
One exception has been the introduction of fully or semi-automated control systems by which discharge measurements and the division of water at canal junctions are controlled and adjusted, either hydraulically (e.g. the French Neyrpic equipment) or electrically, and either at the site of the structure or by remote control from a central control station. Most of the developments in automation and remote control originate from the U.S.A., (e.g. ERIE and DEDRICK 1976). At present, the actual use of such systems is very limited, being confined almost entirely to the U.S.A., France, and Australia. Some of these innovations, however, might well be a realistic option for many developing countries. A (semi-)automatic control of the conveyance and distribution systems, in particular, can facilitate and improve operations, thereby saving water and raising irrigation efficiencies.
A more widespread development in the fields of conveyance and distribution has been the increasing attention given during the last decade to operation and maintenance (popularly known as O and M) and to the corresponding elements of organisation and management (ASCE 1973, ICID 1978). Unfortunately, much of the literature on this subject consists of detailed, descriptive case studies or is of a vague, general and 'open door' kind. It has produced little new information that could be effectively used to improve the performance of existing schemes or the design of new ones.
The greater concern for O and M was induced by the growing awareness that many of the schemes, old as well as relatively new, performed rather poorly. An obvious neglect of maintenance was the most visible symptom of this state of affairs. Gradually, the rehabilitation of irrigation schemes became a central issue. It has even gone so far that the major financing agencies now give first

consideration to the rehabilitation of existing schemes rather than the creation of new schemes. As can be seen from Table 5, roughly half of the irrigated area in the developing countries is now in need of minor or major rehabilitation works.

Commonly taken as a parameter for the operation of a scheme is the efficiency with which the water is used. Applying this parameter, the ICID survey on irrigation efficiencies provided convincing evidence of poor project performances. The efficiencies of conveyance and distribution networks appeared to be disturbingly low, especially for projects smaller than 1000 ha or larger than 15,000 ha. Figure 4, based on data from the ICID survey, illustrates the relative magnitude of volumes of water flowing through an 'average' irrigation system.

The survey also revealed that part of the losses are due to seepage and leaking from canals and structures, but that, depending on the method of water distribution, a far larger part may be due to operational practices. Detailed investigations into the magnitudes and kinds of losses were made in Pakistan by TROUT (1979) and by TROUT and BOWERS (1979). In practice, the efficiencies for conveyance and distribution systems with rotational water distribution often appear to be less than 60 per cent. If one compares this percentage with the percentages for field application efficiencies in Figure 3, one could conclude that

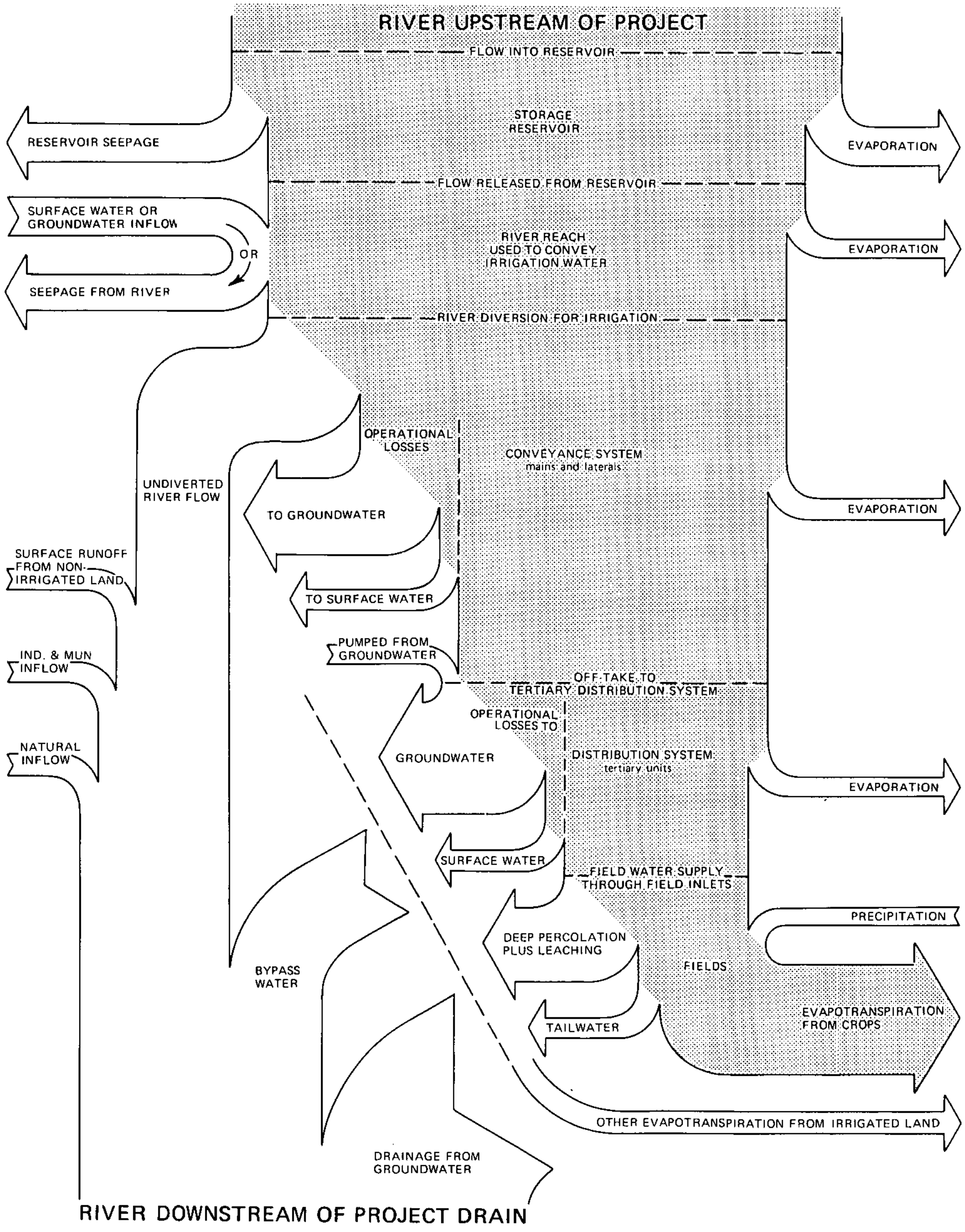


Figure 4.
The relative magnitude of volumes of water flowing through an 'average' irrigation system (BOS 1979).

Table 5.
Importance of rehabilitation (FAO 1977).

Region	Existing irrigation	Renovation and improvement		Areas to be covered by new irrigation	
	area 1000 ha	area 1000 ha	costs 10^6US \$	area 1000 ha	costs 10^6US \$
Africa[1]	2,610	783	444	960	2,616
Latin America	11,749	4,698	2,106	3,101	6,512
Near East[2]	17,105	9,789	6,263	4,295	11,947
Asia	60,522	29,718	13,756	13,848	40,554
Total	91,986	44,988	22,569	22,204	61,629

[1] excluding N.E. Africa
[2] including N.E. Africa

extra care devoted to improving conveyance and distribution could bring about a significant improvement in the overall efficiencies of water use. Similar conclusions were reached by several authors for projects in east Asia (IRRI 1978). They concluded that, for many projects, problems of water distribution were greater in lateral and sublateral canals than at farm level.

In line with the above considerations, literature has always stressed the importance of adequate facilities for the measurement and regulation of discharges and for appropriate communications. All too often, however, facilities to measure discharges are either inadequate or absent altogether, not only in older projects, but also in new ones. And as for communications, such simple measures as a telephone network and clear instructions and forms for the ditch riders, gate operators, etc, are not always provided, even though they can significantly improve operations. Although advances in these fields have not been exactly innovative, they have resulted in a better understanding of these matters.

controlled conditions. Hence, for the study of pracitical drainage problems, one should not rely

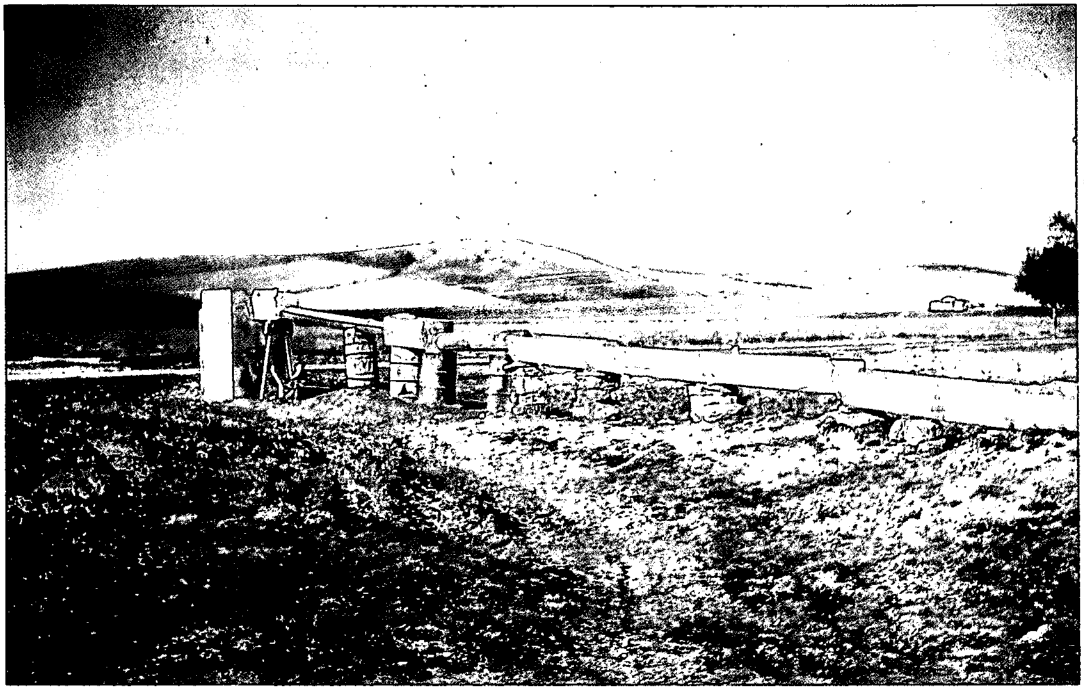
About the same can be said of the influence of the water distribution method on the operation of a scheme. In the IRRI publication, mentioned above, interesting information is provided on staggered and rotational irrigation in relation to such matters as farmers' cooperation, yields, operational problems, and efficiencies. A general conclusion from these articles is that most of the results are determined by local circumstances and may not be generally valid. Of course, this also holds for investigations such as those of LEVINE et al. (1976) in Korea, which report increased yields as a result of rotational irrigation instead of continuous supply.

Another matter related to the distribution of the irrigation water deserves mention. Till the end of the sixties, it was common practice not to construct, or even to design, the canals and structures within the tertiary unit. Water was provided by the project as far as the turnout structure from the main or lateral canal system, and the farmers were supposed to be responsible for implementing the remaining downstream works. In many cases this appeared to be beyond their capacities. Thus, the expensive dams, diversion structures, and conveyance systems were only partly used and by far not as effectively as had been optimistically envisaged in the feasibility studies.

As a result, project planning has been giving more attention to the implementation of the necessary works at tertiary unit level. Discussions are still continuing, however, as to how far the project should go in providing these facilities (see articles by de Wolf and Kortenhorst in this book).

Project performance

As we have already observed, irrigation projects



Downstream of the conveyance system, construction of the canals should not be left to the inventiveness of the farmer.

frequently fail to reach their original objectives. We pointed out two major symptoms of the poor performance of irrigation systems: the deterioration of the infrastructure (Table 6) and the low irrigation efficiencies (Figures 3 and 4). The real reasons behind these symptoms are mostly very complex and difficult to trace. It is known that socio-economic conditions can be a serious constraint: they include cultural attitudes and habits, resistance to change in farming methods, land tenure situation, transport and marketing problems, low product prices, and inadequate credit systems (See also article by Kortenhorst in this book). Many of these factors are beyond the control of the scheme management and certainly beyond that of the irrigation engineer. In the field of agricultural problems, however, management can exert an influence and possibly improve matters by appropriate extension activities on such subjects as proper land preparation, correct handling of irrigation water, adequate fertilizer application, and effective weed and disease control.

It should also be realised that regional, national, and even international politics can exert an influence on an irrigation scheme and thereby affect its results, also in a negative sense. Politically-based decisions at various levels on the construction of new projects, fund allocations for O and M and the organization thereof, and the possible rehabilitation of projects, do not by any means always create conditions for optimum development.

All this is known and everybody involved in irrigation has his own ideas about where the real bottlenecks lie. Strangely enough, however, systematic evaluations of irrigation project performance are rarely undertaken, at least not those evaluations which, besides providing information on what happens, also consider how it happens, why it happens, and what can be done to improve the situation.

The ICID survey (BOS and NUGTEREN 1974) and the studies commissioned by the World Bank and conducted by BOTTRALL (1978) are to our knowledge the first systematic attempts at comparative project evaluation. Bos and Nugteren discuss project lay-out and design, water supply and application, O and M, and water charges. Bottrall evaluates the financial, legal, and economic constraints and discusses aspects of O and M, all within the context of the socio-economic and agricultural boundary conditions mentioned earlier.

Obviously, there are many forces beyond the irrigation engineer that influence the performance of an irrigation scheme. Adequate water management is only one of the requirements for good performance, but, being such an essential one, it should not be hampered by shortcomings in the planning and design of a scheme. In our opinion, such shortcomings occur more often than is generally realized. A commonly heard statement is that 'technically, all is known that is needed to design a good scheme, but the real problems are ...'. Experience has shown, however, that technical deficiencies occur quite frequently. Nor are design concepts always in accordance with local conditions, taking little account of farmers' con-

Maintenance problems evoked by incorrect design.

straints or of the management required for O and M.

Schemes, requiring from farmers and management personnel, skills that they cannot be expected to acquire easily and quickly, are simply incorrectly designed. Local socio-economic constraints should be regarded as basic data, just as water, climate, and soil conditions are. This would be more realistic than accusing those constraints of hindering the proper performance of a 'technically well-designed' scheme. Let us give some examples:

- It is common practice, although not always explicity recognized, to design a scheme on the rule-of-thumb of a 80 per cent year. This means that in an average of one year out of five the designed volume of water will not be wholly available. This is done without taking into account specific conditions of river regime, project objectives, crops, incomes etc. In many cases other criteria could well be more benificial (LIVINGSTONE and HAZLEWOOD 1978).
- Irrigation systems are frequently designed for a 24 hour per day irrigation, 7 days a week, whereas in practice this is simply not accepted.
- Duration and flow rate of field irrigation are not well adapted to the irrigation method and soils, and not suited to the local conditions of available labour, skills, and attitudes.
- The designed irrigation schedule and the resulting rotational schedule are too complicated for the (limited) management abilities.
- The cropping patterns (and consequently the water requirements) are in reality so different from the designed ones that the system (and only consequently the management) cannot handle the situation.
- Advanced technology is introduced where one cannot reasonably expect it to be properly used.
- Measuring and regulating devices are too complicated, vulnerable to misuse, or totally lacking.
- The hydraulic flexibility of the system is less than required to supply water uniformly.
- A drainage system is not included in the project design.

In this context it is observed that engineers often yield to the pressure to produce a feasibility study that shows an internal rate of return of 8 per cent or more. To achieve this magic figure, essential parts of the irrigation plus drainage system are deleted or underdimensioned, with little thought given to the risk that this might further diminish the viability of the project.

More than fashionable talk is required

We have seen that remarkable results have been achieved in irrigated agriculture, especially in the expansion of its area. Certainly, it is possible to design and implement large-scale irrigation schemes in a relatively short time. Apparently, however, it is less easy to do it in such a way that the expected results are actually achieved.

The performance of irrigation projects, in the context of their agricultural, economic, and social objectives needs urgent improvement. But we have also seen that the most conspicuous developments in irrigation technology have hardly contributed anything to such improvement.

How, then, can performance be improved? In examining this question, it is convenient to divide it into two parts: (i) the better functioning of existing schemes and the rehabilitation of poorly maintained schemes, and (ii) the design of new schemes.

Evaluation studies on operation and maintenance can supply answers to point (i), especially with regard to poorly maintained schemes. At present, schemes are still being reconstructed to their original state without a proper evaluation of the causes that led to their deterioration. The long-term involvement of monitoring teams can help greatly in discovering the causes of poor operation and finding ways to remedy them. The work of the Colorado State University in Pakistan (CSU 1978) is a fine example of efforts in this field.

On point (ii), the design of new schemes, it is observed that the disappointing experiences with large schemes have been calling for a shift in policy towards small-scale or minor irrigation. This is often advocated on the basis of isolated arguments and vague ideas rather than on comprehensive and well-balanced investigations. But there is more to this question than the implied assumption that small scale is automatically identical with appropriate technology, that it will better reach the small farmer, and will therefore better and sooner solve all social, economic, and agricultural problems related to food shortage and poverty. Unfortunately, it is beyond the scope of this article to further contribute to this discussion. Certainly, a small-scale project will be an appropriate solution in specific circumstances and this option should be carefully studied. On the whole, however, and for a long time to come, large-scale projects will retain their importance as they involve a greater number of people, greater areas, a greater potential for food production, and greater financial investments.

Since the beginning of the 1970's (e.g. FAO 1972) two points have been regarded as essential in the design of new large-scale schemes:

- Studies and design should be based on an integrated approach, instead of on a number of isolated findings.
- The role of the farmer should be given a key place in all considerations; the design must take into account how a farmer (or group of farmers) can or will use the water.

Since then, a consensus has grown in support of these ideas. It is commonly agreed on 'what' should be done, but the question of 'how' remains a problem. No one seems entirely sure how to translate these ideas into terms of practical action.

The concept of an integrated approach is still vague. Multidisciplinary teams have become commonplace, but their attempts at a real integrated approach are unsystematic and poorly structured. Operations research, systems analysis, and similar techniques have found some application, but in most cases they deal more with water resources management and engineering in a wider sense. Only a few publications (e.g. WINDSOR and CHOW 1971, SMITH 1970, CUNGE and WOOLHISER 1975) treat the irrigation system as such, but even they are concerned more with the economic or purely technical aspects of the system. Nowhere, as yet, has the key role of the farmer progressed beyond mere lip service or descriptions of 'present situations'. The contributions from socio-economists and sociologists continue to be too limited and too isolated, and the problem remains how to give their contribution an operational place within the team.

Without pretending to know the answers to all problems, we think that a systematic and profound reconsideration of all the phases of the irrigation design process would be useful. A wealth of knowledge is available on all these phases: the determination and selection of cropping patterns, field area and layout, method of field application, system of water distribution and irrigation schedule, channel capacities, system and network of measurement and regulation structures, flexibility of water supply and distribution, and phasing of the implementation. But the existing knowledge is scattered and fragmentary. It needs to be collected, reshuffled, and in many cases made operational. Special attention needs to be given to the interrelationships between these factors, and to their relations with the project objectives and priorities. Step by step, throughout each phase, constant thought must be given to the relations between local resources and constraints and socio-economic and management factors. All this has to be done with the ultimate aim of designing a viable scheme – not one that is economically feasible on paper but will perform disappointingly in real life and will have to be rehabilitated within ten years of its construction.

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Rice cultivation and water control

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Importance of rice

Rice, wheat, and corn are the three leading food crops in the world and together they supply about 50 per cent of all calories consumed by the human race. In terms of area harvested each year, wheat is the leader, with 215 million hectares, followed by paddy rice with roughly 140 million hectares. The 200 million tons of milled rice produced each year provides the major source of calories in the diets of almost 40 per cent of the world's population. Throughout vast areas of the less well-fed world, rice provides 75 per cent of the total calorie intake and almost 60 per cent of the protein intake. Rarely does either wheat or corn approach these figures (HUKE 1976).
Rice is a crop raised chiefly on small farms, most of them less than one hectare. The farm population dependent on rice totals at least 1200 million people. The vast majority of rice farmers live close to the margin of existence. A poor harvest can mean serious hardships to the individual family; any reduction in yield over a broad area can lead to disaster.

Role of water

The role of water in rice cultivation is a dominant one. During the major part of its development, most rice is grown with a layer of impounded water on the surface of the fields. Long ago, Asian farmers found that they could till the soils with their simple implements only when the soils were saturated. They therefore erected bunds to keep water on the fields during tillage. The water level also provided them with a convenient guide to level the soil surface. The soil treated in this way was transformed into a liquid mud that could retain more water than a normal soil. Fortunately the rice plant is adapted to wet conditions and even derives benefits from them.
The benefits of keeping a water layer of 5 to 10 cm on a rice field are (van de GOOR 1974):

- The continuous water supply means that the roots are surrounded by water so moisture stress will never occur
- The cover of water in the first 4 to 6 weeks after sowing or transplanting helps to control weed growth
- The protective water layer prevents splash erosion and the formation of a surface crust
- The water layer acts as a temperature regulator and creates a favourable microclimate.

The rice plant tolerates, but does not require, excessive quantities of water. It is more the attendant circumstances that make the use of water higher with rice than with most other crops. Nevertheless, rice is extremely sensitive to moisture stress and yield reductions can be expected as soon as the root zone is less than saturated. The impounded water is therefore of great value in avoiding this risk.

Land preparation (puddling)

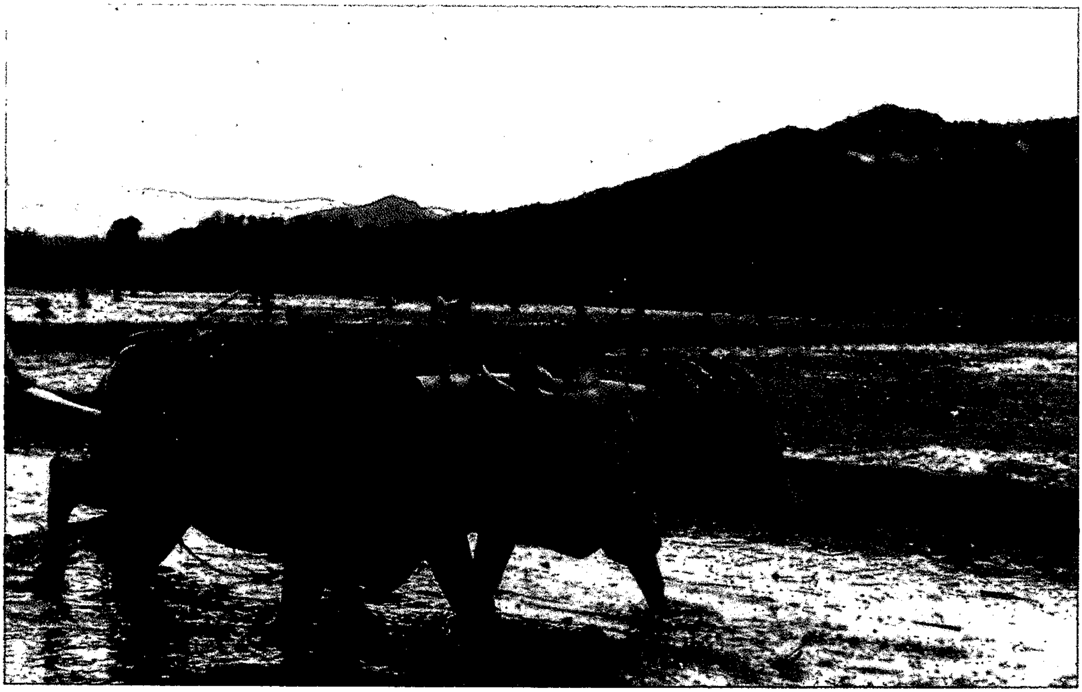


Table 1.
Yield reduction (kg/ha) in relation to stress days and nitrogen application (based on data from WICKHAM 1973).

N-application 80 kg/ha			N-application 40 kg/ha			N-application 10 kg/ha		
S_1*	S_2*	Yield	S_1	S_2	Yield	S_1	S_2	Yield
0	0	4136	0	0	4092	0	0	3765
10	0	4216	10	0	3956	10	0	3467
0	10	3624	0	10	3364	0	10	2821
10	10	3272	10	10	3012	10	10	2523

* S_1 = stress days during the vegetative growth stage (tillering)
S_2 = stress days during the generative growth stage (panicle formation)

The effects of moisture stress are even more pronounced in the modern high-yielding varieties developed by the International Rice Research Institute (IRRI) in the Philippines. These varieties have a short growth duration (120 days from transplanting to harvest), a short sturdy column (110 cm long at maturity), and are insensitive to the photo period (their time of flowering is not dependent on specific length of daylight). When these varieties are grown, they can produce two reliable high-yielding crops of rice a year. But they react sharply to shortcomings in water management!
WICKHAM (1973) demonstrated the influence of moisture stress on yields of modern rice varieties, using the concept of stress days (days in excess of three for which the field was continually without standing water). He also showed that extra nitrogen can compensate to a certain extent for stress effects during tillering (Table 1).
Good water management for rice must not only ensure that a layer of water is kept on the field, it must also ensure that the layer is not too deep. Table 2 shows the reduction in yields when water depths are excessive (ILRI, in preparation).
It is obvious that rice does not require drainage in the same way as other agricultural crops. Nevertheless, good water management also includes the timely removal of water, not only to prevent too deep water layers but also to allow fertilizing, to create good ripening and harvesting conditions, and to dry the soil between two successive rice crops.
The flooding, tillage, and puddling of the land has certain consequences for the chemical, biological, and physical conditions of the rice soil (van de GOOR 1974). One of these consequences is the nutrient supply, especially that of nitrogen. Because of waterlogging, the root zone is in a reduced state and nitrates, if applied, would be lost through volatilization. This problem can be overcome by placing ammonia fertilizer in the reduced zone.

Table 2.
Relative yield (%) for period of 0–40 days and 40–70 days after transplanting (short-stem, 'modern' varieties).

Period	0–40 days			40–70 days		
water level above	duration of water level					
ground level	1 day	5 days	10 days	1 day	5 days	10 days
125–150 mm	99	95	94	100	99	98
300–325 mm	95	68	58	96	85	76
575–600 mm	91	41	21	86	45	19

Irrigation for rice

In the traditional rice-growing countries, all of which lie within the tropical monsoon belt, the rice production season starts at the beginning of the rainy season and both seasons last for about five months. As the rainy season comes to an end and rainfall ceases, good conditions are created for ripening and harvesting of the rice crop.
Supplementary irrigation can be most useful in these areas to supply water during the period of land preparation (puddling). The demand for water is high at this time and the onset of the rainy season is erratic. Supplementary irrigation thus helps to maintain a strict cultivation calendar.
Nor are the amounts of rainfall the same from year to year; in years of lower rainfall, supplementary irrigation can make up for deficits.
In areas where supplementary irrigation has been successfully introduced, it has frequently promoted full irrigation schemes that allow double cropping of rice, i.e. a second (dry-season) crop can be grown as well.
Rice is also produced in areas that do not lie within the tropical monsoon belt. Examples are the Nile Delta, Pakistan's Sind Province, northern Hokkaido, parts of the Sahel, and Manchuria. In these areas, temperatures are high, relative humidities are low, and the potential evaporation rates are among the highest in the world. Water demands for a rice crop in these areas are almost double the needs of the same crop in the humid tropics. Without irrigation, no rice production would be possible.
Of the world-wide total of 140 million hectares on which rice is grown, some 59 million hectares now have some form of irrigation (EARLY et al. 1979). This constitutes a large proportion of the rice-growing area and is a proportion that can only be expected to grow in the future.
Considering the vital role of rice in feeding so many of the world's population, considering also the dependence of the rice crop on good water management, and considering further the vast numbers of small farmers who are – or will be – involved in rice irrigation schemes, let us take a critical look at these schemes and at the way the farmers function within them.

The tertiary unit

An irrigation scheme begins at the source of its water. This source may be a river, a reservoir, or a pumping station. The water is conveyed from its source through a main canal, from which it may be diverted into secondary canals, and proceeds further until it reaches a tertiary offtake. A tertiary offtake is a structure that diverts water from a main or secondary canal to supply a tertiary unit. A schematic of an irrigation scheme is shown in Figure 1. The terminology used here is that advocated by the International Commission for Irrigation and Drainage (BOS 1979).
In its journey from the source to the tertiary offtake, the water is the responsibility of the scheme authorities. When it passes through the tertiary offtake and enters the tertiary unit, it enters the domain of the farmers. Within the tertiary unit, which contains a number of farms, the group of farmers are responsible for distributing the water through the tertiary and quaternary canals to the farm inlets, after which each individual farmer assumes responsibility for the application of the

Fields of young paddy.

water to his fields.

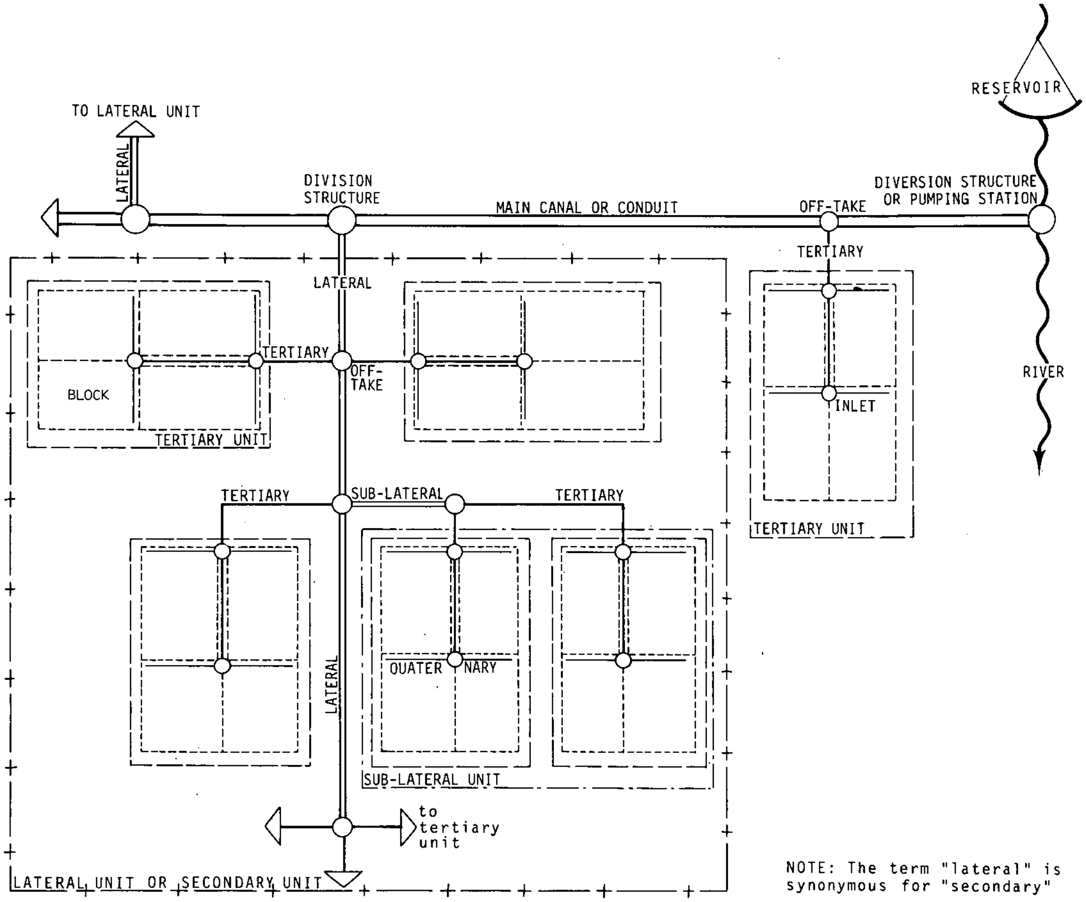
As rice farms are usually very small, the tertiary unit of a rice irrigation project is likely to contain a large number of farms. Ensuring that each farm receives its equitable share of irrigation water demands a collective effort on the part of the farmers. A well-designed tertiary unit will alleviate many of the problems of water distribution.

Design

The task facing the designer of an irrigation scheme is a highly complex one, combining as it does a myriad of technical, economic, agronomic, and social factors. Basically, however, his task is to create a layout that achieves two things: it must use the available water as efficiently as possible, and it must enable an equitable distribution of the water among the farmers.

If an irrigation scheme is to be designed for hitherto virgin land that is being opened up for settlement, the designer's problems will be relatively few. The location of the source of irrigation water and the topography of the area will largely decide the layout of the main irrigation and drainage canals. Into this layout, the tertiary units must be fitted.

If irrigation is to be introduced into an already settled area or if an existing irrigation scheme is to be rehabilitated, the design may be greatly complicated by problems of land ownership, land



NOTE: The term "lateral" is synonymous for "secondary"

Figure 1.
Schematic of an irrigation scheme (BOS and NUGTEREN 1974).

tenancy, or the fragmentation of holdings.

But whether the irrigation scheme is on 'old' or 'new' land, a wise designer will consult with the farmers before proceeding with the design of the tertiary units. The size of the tertiary unit, the method of water distribution that will be adopted, and how its delivery will be scheduled are all matters that deeply concern the farmer. The designer should provide the farmers with a tertiary unit that they can handle with ease andefficiency. At this stage it can also be decided in how far the farmers should participate in the construction of the tertiary facilities. Their involvement in these activities càn be a major factor in creating the cooperative spirit so vital to the success of irrigation schemes. Not only does it promote the feeling among the farmers that the scheme belongs to them, it also helps to keep costs down. The farmers should not, of course, be burdened with tasks that are too onerous. Land clearing, land levelling, and road construction will usually be beyond their capacities.

As observed by NUGTEREN (1967): 'A tertiary unit is not only a key element in the design of an irrigation project, it also constitutes an organizational entity of great value for the social structure of the farming population'.

But leaving social considerations aside, the technical aspects of tertiary unit design will involve decisions on the following three items:

- the water distribution method (continuous or rotational)
- the size of the irrigation module, i.e. the stream flow to be provided to each farmer
- the size of the tertiary unit.

Water distribution

In many rice growing areas, irrigation is provided by a system of continuous flow. Throughout the crop season, water flows continuously from the tertiary and quaternary canals into the rice fields. The distributary canals always contain water and each farm receives a share of the total flow in proportion to its area. This system is widely applied where rice is grown in the traditional way.

Continuous irrigation, however, often means:

- tertiary offtakes lacking devices for measuring water
- poor facilities inside the tertiary unit for measuring, distributing, and regulating water flows
- a lack of clearly demarcated quaternary units and canals served by a group inlet
- a high degree of plot-to-plot irrigation with farmers close to the tertiary canal in a good position for both irrigation and drainage
- a relatively large irrigation stream flow entering the tertiary unit
- a low efficiency in water application
- problems in times of water scarcity, particularly in downstream fields.

Obviously, with so many shortcomings, equitable water distribution within the tertiary unit is no simple matter.

Under rotational irrigation, water is also drawn continuously from the tertiary offtake but it is supplied to the farms on a schedule of rotational flow. Rotational irrigation thus means a subdivision of the tertiary unit into quaternary units, with the quaternary canals carrying water only part of the time.

Rotational irrigation demands accurate measurements of the stream flow, proper facilities for distributing the flow, and a highly disciplined organization of the farmers. It thus offers better opportunities for water control and will do much to ensure equitable water distribution. It also enables farmers to time fertilizer applications and weed control (THAVARAJ 1975). Rotational irrigation may also mean savings in irrigation water. Some researchers in Taiwan claim that rotational irrigation uses 30 to 50 per cent less irrigation water (DE DATTA et al. 1973). It is often recommended in locations where it is desirable to irrigate as large an area as possible with a limited water supply.

The absolute advantages of rotational irrigation have been questioned by researchers in the Philippines (WICKHAM and VALERA 1978; MIRANDA and LEVINE 1978). Admittedly, rotational irrigation brings with it higher project costs for the provision of tertiary unit facilities, and also places heavy organizational demands on project management and farmers alike, especially in large projects. Nevertheless, there seem to be more points in favour of rotational irrigation than against it.

Irrigation module

In the practice of gravity irrigation, the quantity of water that can be handled adequately by one farmer is known as the irrigation module (and also as *main d'eau*). The module may vary roughly between 15–60 l/s. The choice of the appropriate module depends on the field irrigation method (basin, border, furrow), the slope of the field, soil conditions, field dimensions, and the skill of the farmer.

Rice irrigation uses the 'basin' method and a module of around 30 l/s is considered acceptable. The size of the module may be higher or lower than this figure, depending on the facilities that are available to control the flow. A very low module of, say, 1 l/s would not be sufficient to flood the basin, while very high modules would mean excessive water use.

Size

The crucial factor in deciding the size of a tertiary unit is how the collective delivery of water can be successfully organized. When the farmers have a stable social structure because they belong to a strong village community, the distribution of water may present no problems and the tertiary unit can be larger. In such areas, a tertiary unit may contain up to 50 farms, but of course the farm size plays a role as well.

In new irrigation schemes, where the farmers may lack a strong community spirit, the design should be based on a more individual handling of the water distribution and the tertiary unit should be kept small. It should serve no more than 10 to 25 farms.

Generally speaking, the larger the tertiary unit, the greater will be the operational difficulties and also the greater will be the losses of water in the distributary canals. If units are too large, farms at the tail end of the tertiary canal are apt to suffer from poorly controlled water supplies further upstream.

A direct relationship exists between the size of the tertiary unit, the irrigation module, the water distribution method, the number of farms, and the size of the farms. This will be demonstrated by a simple example.

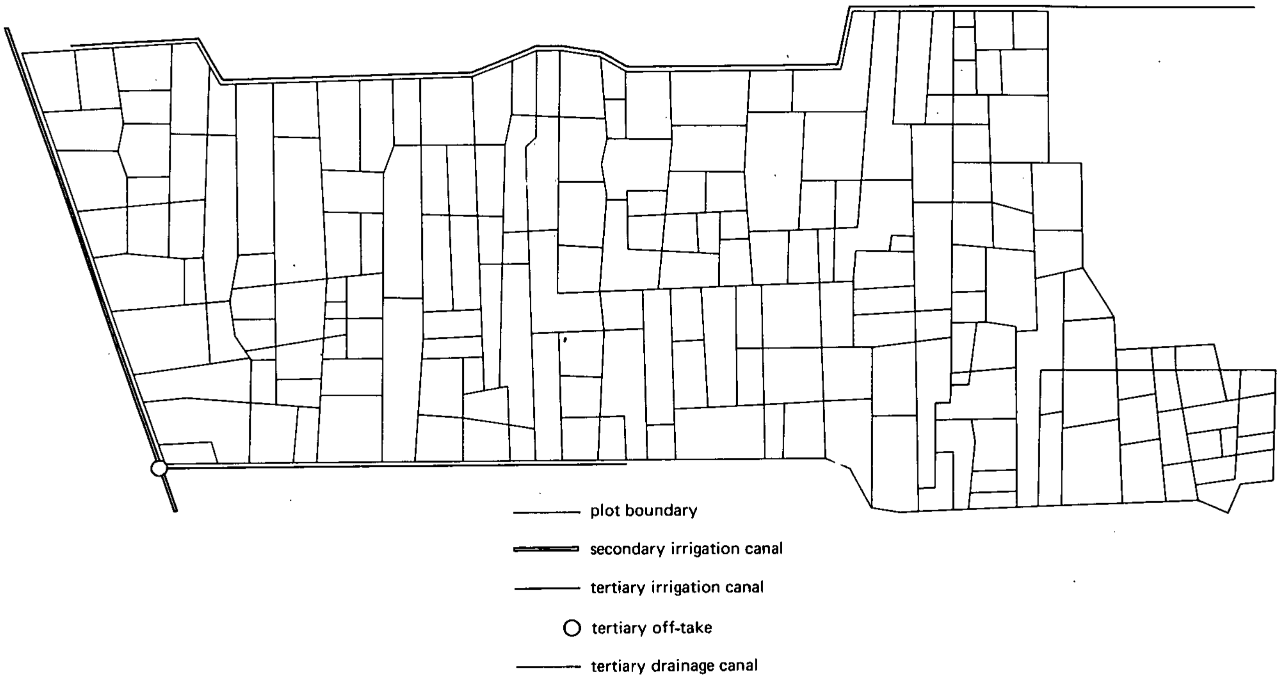
Let us assume an irrigation module of 35 l/s, which is an acceptable module for rice. If the daily irrigation water requirement is 10 mm (or 10/8.64 l/s/ha), the irrigation module can supply water to a tertiary unit of $\frac{35}{10/8.64}$ = 30 hectares.

If the farm size is 1.50 hectares, the tertiary unit will contain 20 farms. If these farms are served by a system of rotational irrigation with an irrigation interval of, say, 10 days, the irrigation module can supply 2 farms each day with the 100 mm they need to meet their requirements. Each farm may receive either half the module for 24 hours or the whole module for 12 hours.

With a farm size of 0.50 hectares and the same irrigation module, the tertiary unit will still be 30 hectares but will now contain 60 farms. With the same rotational schedule of 10 days, distribution

Simple off-take from a main canal.

Figure 2.
Tertiary unit for rice cultivation in Sulawesi, Indonesia.



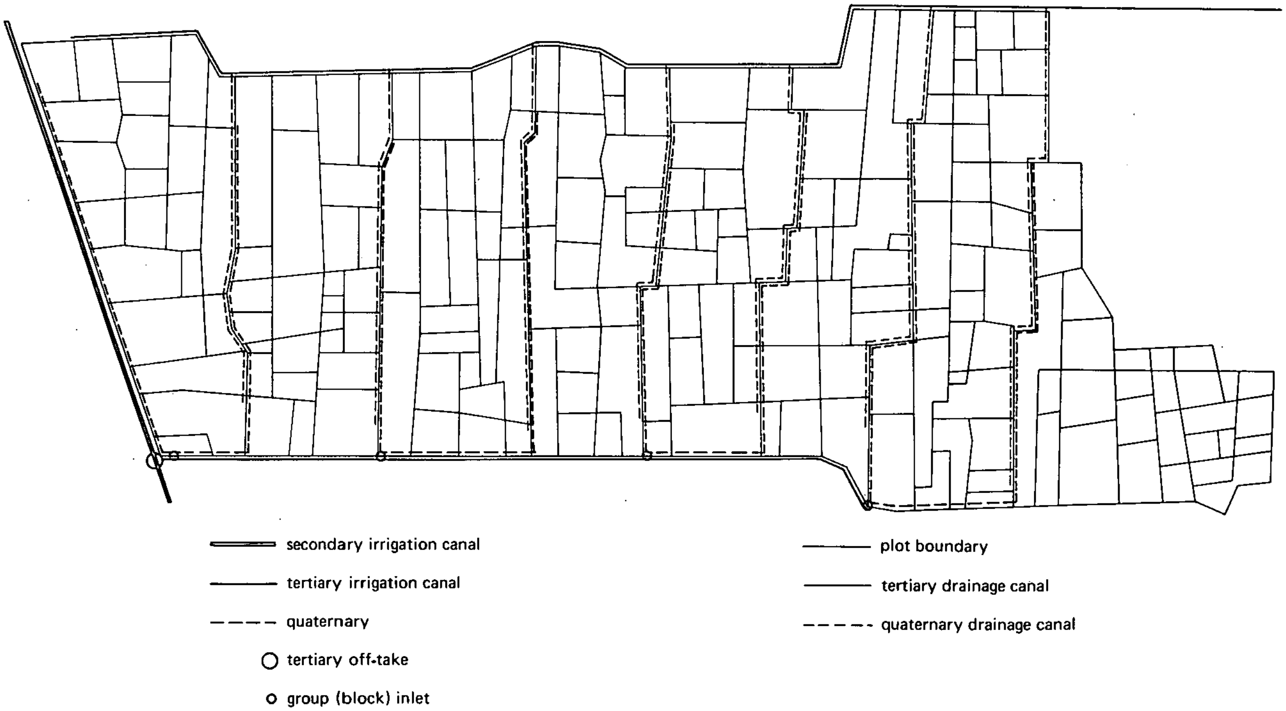


Figure 3.
Additional tertiary unit facilities for layout in Figure 2.

A complicated system of water conveyance and distribution. Division structure and tertiary offtakes Lamasi area, Sulawesi (Indonesia).

becomes more complicated as 6 farms must receive the module on one day.
With an irrigation module of 70 l/s, the size of the tertiary unit will double. This may be required in certain projects for economic reasons or to give more flexibility to the design. In such cases the tertiary unit can be split in two and the tertiary canal provided with a division structure immediately downstream of the offtake.

Examples

The layout of a complex tertiary unit in a rice irrigation scheme in Sulawesi, Indonesia, is shown in Figure 2. Originally (about 1940), the size of the tertiary units was between 200 and 250 hectares. The scheme was rehabilitated in 1973 and was provided with extra secondary canals and a larger number of tertiary canals and offtakes. The tertiary units were reduced to 110 hectares. The average density of the conveyance canals was 6 m per hectare.
Although reducing the size of the tertiary unit by approximately one half is quite an improvement, it remains doubtful whether good water management can be achieved within the unit. The quaternary canals have not been included in the design, and it is difficult to see how more than 100 farmers could cooperate effectively in distributing the water. Even with the addition of 1100 metres of tertiary canals and 4500 metres of quaternary canals as shown in Figure 3, the size of the tertiary unit, its configuration, and its facilities would seem to militate against good water management.
At the other end of the scale is a tertiary unit in the Kou Valley rice irrigation project in Upper Volta (WARDA 1975). There, the tertiary units comprise 12 hectares and have 12 farms within their perimeters. The project, which totals 1100 hectares, has a very high density of conveyance canals: 80 metres per hectare.
A dense network of conveyance canals usually corresponds with small tertiary units. It also means higher costs and a greater loss of land.
The average density of conveyance canals in nine rice irrigation projects (5 in Indonesia, 3 in the Philippines, and one in Malaysia) is 13 metres per hectare, with a minimum of 6 m/ha and a maximum of 22 m/ha (KEE SEUNG PARK 1975).

Need for a phased development?

A question that arises particularly in the rehabilitation of irrigation schemes is how intensive should be the measures that are taken. It is a question that certainly arises in areas where holdings are excessively fragmented because fragmentation unnecessarily complicates water management. A farmer who has fields in more than one tertiary unit, for instance, must observe more than one irrigation schedule, which is a burden both to him and to the project authorities. This is only one of the many problems that irrigated rice technology faces as a consequence of fragmentation (PAL 1978).
In Japan, rice irrigation development plans incorporate a detailed package of tertiary unit facilities, intensive on-farm development, and a programme of land consolidation, with land consoli-

Figure 4.
Tertiary unit in Northern Chao Phya, Thailand, prior to improvement (adapted from NEDECO/ILACO 1973).

Figure 5.
Low cost, less intensive tertiary unit improvement in section of area of Figure 4 (adapted from NEDECO/ILACO 1973).

dation regarded as vital in creating optimum conditions for water management (UCHIHARA INTERNATIONAL AGRICULTURAL TRAINING CENTRE 1975).

Land consolidation also forms an essential part of irrigated rice development in the Northern Chao Phya area of Thailand (KARUNYAKAN 1978; NEDECO/ILACO 1973). The lack of tertiary unit facilities (see Figure 4) keeps rice production low in the wet season and double cropping can be practised only to a limited extent. Rehabilitated areas are provided with a completely new network of irrigation and drainage canals and farm roads. Each individual field has an irrigation inlet (if possible direct from the tertiary canal), a drain outlet, and access to a road. The re-allocated plots are rectangular. Land levelling is included as a vital part of the operation. Where the programme has been implemented, yields have increased dramatically and double cropping has become common practice.

Investment costs are not excessively high, but the time required for planning, designing, and implementing is very long. The annual output is less than 1000 hectares. This is creating an uneven distribution of benefits among the farming population. The question arises whether it would not be better to take less intensive measures that could be spread over a wider area and benefit a larger proportion of the people.

In the present situation (without improvement)

Figure 4.

Figure 5.

A good yield?
Temporary storage of recently harvested paddy in Pemali-Comal area, Java (Indonesia).

there is a complete lack of drainage canals, no internal road network, and the tertiary units are very large (between 200 and 250 hectares). A reasonable partial development could be achieved by the layout presented in Figure 5.

This layout would reduce the size of the tertiary unit to around 70 hectares, improve drainage, reduce plot-to-plot irrigation, and enhance the irrigation efficiency. And it would cost only 25 per cent of the costs of the intensive improvements. What is more, it would require no detailed cadastral survey beforehand. (To avoid sharp curves in the canals, small areas of land could simply be exchanged among the farmers). Partial improvement would mean a fast rate of development over a larger area and better distributed benefits.

When various options are open, it would seem wise to start with a relatively simple programme covering large areas in a short time. One can always return later with a more complete programme.

Intensive development is also found in India, where a full-scale reconstruction of land surfaces and water distribution structures is being combined with an exchange of ownership units by a consolidation of holdings and a realignment of boundaries. This is known as the Kota Method, after the town in Rajasthan where it was first implemented. Here, too, the message would seem to be 'Study the alternatives'. As observed by WADE (1975): 'The choice of technique in irrigation command area development must be adapted to the rate at which land development is expected to proceed. The next few years will see less comprehensive, less elegant approaches in use with more attention to local variations; the Kota Method will be one end of a range of possible alternatives'.

Another school of thought which advocates a phased development but for a different reason is represented by BOTTRALL (1978). He argues that the technology introduced at the beginning of a project may be too sophisticated for the relatively modest requirements of the farmers, and that the operation and maintenance of the project may be beyond the capacities of local staff. Whether this represents a sound reason for making a simple start instead of a more sophisticated one (or the best) is difficult to say. A concerted effort in training could possibly do a lot to remedy the situation.

Nevertheless, the skills of the farmers and the competence of the project management must, of course, be taken into account. When the choice is being made between continuous and rotational irrigation, for instance, skills and competence will be highly relevant.

To quote IRRI (1973): 'Choosing an appropriate level of sophistication for the design of a system, and maintaining a proper balance between physical design and human management capacities within it are difficult tasks that demand considerable attention'.

Conclusions

In rice irrigation schemes, the need for better water control at on-farm level is being increasingly recognized. Irrigation authorities have become aware that their task extends beyond the mere design and construction of the conveyance network. Whereas formerly they left the design of the tertiary unit and the construction of its facilities to the farmers, they are now recognizing that the tertiary unit is the 'heart' of an irrigation scheme and is far too important to be left to chance. In some places, on-farm development has become almost a slogan.

The authorities are also realizing that the smooth operation of the tertiary unit depends greatly on a spirit of cooperation among the farmers. As this is a somewhat fragile entity, they are now taking an element of human behaviour into account in their designs and are endeavouring to create 'foolproof' tertiary units. The watchword seems to be: Keep it small and keep it simple.

Nevertheless, there is an enormous area of land under rice; there are great variations in soil types and in geographical and hydrological situations; there are millions of smallholder rice farmers, all with varying social and educational backgrounds and all cultivating a small piece of land on which they may be utterly dependent. Hard and fast rules for the design of tertiary units are impossible to give. The design that may be right in one case need not necessarily be right in another. Each case requires individual study and *all* cases require that the farmers be consulted. A remark made at an irrigation seminar sums it up nicely: 'All designers should have to operate the systems they design'.

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Factors affecting the viability of smallholders irrigation

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Introduction

The introduction of irrigation into areas where rainfall is insufficient and unreliable and where irrigation is not a traditional practice has been receiving high priority in recent years. It is a trend that will certainly continue.

Generally speaking, however, irrigation schemes in such areas have been found to contribute little to rural development, notwithstanding and often in plain defiance of the original feasibility expectations. Of course, there are exceptions, mainly in the small-scale sector (BALBO 1975). But all too often, sooner or later, after a seemingly successful take-off period, declining yields, diminishing returns, the growing indebtedness of the farmers, and hence their loss of interest, lead to the failure of the schemes. The blame for failure is usually placed on the farmers, but invariably the true cause is an overall lack of viability of the project design itself – a design that did not permit farmers to adopt irrigated cropping as an integral component of a new, self-sustaining, balanced farming system.

The lack of viability of new irrigation schemes is not seldom masked, especially in the large schemes, by a strict, directive, scheme management *ad infinitum* to safeguard national productivity interests. This actually means a curtailment of the farmers' own farm management responsibilities. It reduces them from being participating producers with family holdings to mere production factors in an estate-type of irrigated agricultural enterprise, of which the survival strategy is based on imposed discipline and centralized execution of essential upstream and downstream farm operations.

Is that what the introduction of irrigation should lead to? Or can project designs be improved so as to place irrigation in the hands of the farmers, where it belongs?

In answer to the first question, suffice it to quote BARNETT (1977) who entitled his study of the 2,000,000 acre Gezira Scheme in Sudan – the best-known example of irrigated production under close supervision – 'An Illusion of development'. This terse qualification is, in my opinion, also applicable to other schemes with a similar set-up.

The answer to the second question should be 'Yes', and it could be, provided that development philosophy became farming-system-oriented instead of, what it still largely is, commodity-oriented. It is in this light that – without the pretension of being exhaustive or of presenting concrete solutions for all problems – I shall attempt to review the factors that affect the viability of smallholders' irrigation schemes.

Farming systems

During the last decades, which were once hoped would be a true development era for the Third World countries, development cooperation efforts – and not only in the field of irrigation – have not made their expected impact. General cognizance is growing in recent years, however, that not the farmer is to blame for this, but instead the inadequacy of his institutional environment. Also being recognized is that the promoted technology usually fits neither into the existing farming system nor into the family living patterns. And yet – for lack of knowledge of the existing farming systems – little is being done to bridge that gap. As stated by ENSMINGER (1977), development should be '...oriented to helping the farmer *as he is* and not as he may some day become'.

'Farming system' is defined here as the whole of activities of a smallholder's family ('those who eat from the same kitchen'), undertaken to satisfy their needs. Those activities can be manifold and be either productive or consumptive. They are interrelated or mutually complementary sub-systems of the whole farming system, all drawing from or contributing to the same family resources. How complex a farming system can be is shown by an example, commonly found in the Sudan Zone of West Africa, where one and the same farming system may include the following sub-systems:

Cropping system 1.	Family 'farms', under the responsibility of the head of the family, mainly for the production of staple food crops
Cropping system 2.	Cash crop 'farms' of individual family members, usually men
Cropping system 3.	Special 'women's fields' for kitchen and local-market crops; the market proceeds are for the women concerned
Cropping system 4.	Home-yard cropping, which – except perhaps for heavy soil preparation work (if applicable) – is usually looked after by the women and the aged family members
Livestock system 1.	Livestock keeping (in areas free of *trypanosomiasis*), with grazing mainly on communal village range grounds, often looked after by young boys
Livestock system 2.	Small livestock and poultry-keeping, in the home-yards
Collecting system 1.	Food gathering and hunting, on communal range grounds
Collecting system 2.	Fishing, in communal waters
Off-farm activity 1.	Home processing and handicrafts
Off-farm activity 2.	Petty trading, almost exclusively by women
Off-farm activity 3.	Seasonal or part-time wage-earning elsewhere; if outside the village, almost exclusively by men
Consumption system 1.	Household and family care (women)
Consumption system 2.	Homestead construction (men)
Consumption system 3.	Social and cultural activities

In the world at large, innumerable other farming systems have developed historically. The most important types have been described by ANGLADETTE and DESCHAMPS (1974), DUCKHAM and MASEFIELD (1970), GRIGGS (1974), RUTHENBERG (1976) and JURION and HENRY (1969). As observed by the last-mentioned authors: 'It is obvious that men have gradually found out by trial and error what forms of production, and in what succession, go best with which ecology'.

The variety of sub-systems, their interdependence, and the relative importance of each sub-system that together make up the overall farming system are determined by the farmer's setting of resources, constraints, and values. This framework of factors, with the farmer as ultimate 'decision centre', is sketched in Figure 1.

All these factors interact, and any one-sided, 'single-theme' influence or intervention from out-

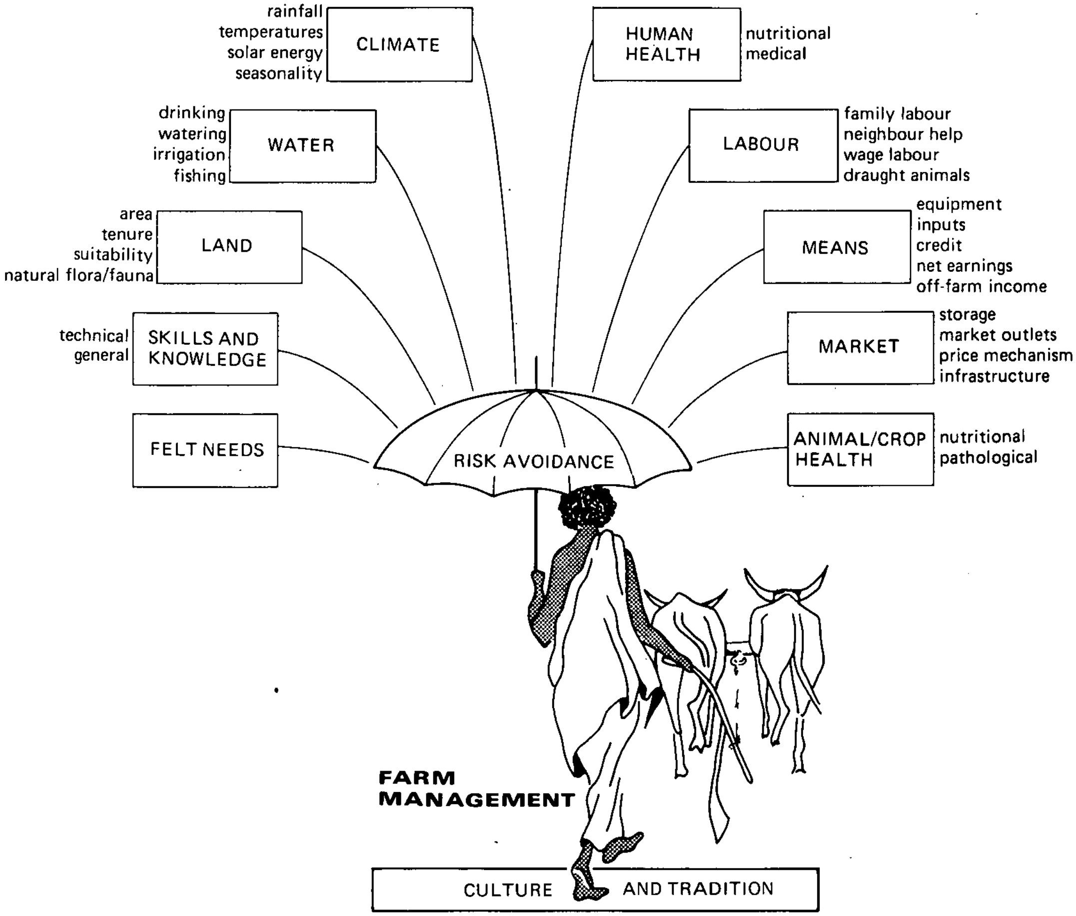

Figure 1.
The farmer's setting of resources, constraints,and values

side, or change from inside (e.g. family expansion), tends to set off a chain-reaction that leaves the farmer with the adaptation problem of how to find a new balance in his farming system.

Well-intended interventions sometimes cause a change for the better in the existing farming system – if the innovation happens to relieve a bottle-neck constraint, as when, say, a crop variety with greater drought tolerance and thereby improved yield stability is introduced; but all too often they mean a change for the worse. Regional food problems, for instance, are quite commonly induced by the (macro-economically) successful introduction of cash cropping (LELE 1975). Any success of such single-theme programmes, made possible by the farmers' enticement to cash money, can within a given framework of limited family resources only be achieved at the cost of the traditional crops, usually food crops, in particular the ones with low market values or low unit yields or those that serve mainly as reserve ('security') crops. Examples of such crops with diminishing importance are plantains in East Africa, various traditional millet species all over Africa, and the sago palm in South East Asia. Even more radical than the, in fact relatively simple, broadening of an existing cropping system with a single additional crop, is water resource development. Well-known is the example of the ruinous effects that the wildcat construction of watering wells and reservoirs, meant for nomadic livestock improvement, is having in the African Sahel Zone on the land because of overgrazing – and possibly even on the climate, as some scientists believe (OTTERMAN 1977). Water development in the Sahel appears hitherto to have been a rather straightforward case of 'anti-development'. The introduction of irrigation, another form of water resource development, is also a very radical intervention. If conceived only on the basis of agro-technical and economic criteria and without adequate knowledge of all other relevant factors, it bears great risks of upsetting the original farming system rather than improving it. For example, how could irrigation be fitted into the farming system in the Sudan Zone of West Africa? With its specific land and labour requirements, what consequences would a new irrigated cropping system have on the other sub-systems? Would irrigated cropping in the dry season be worthwhile if it would leave the farm family no time for their traditional, typically off-season activities such as fishing, hunting, handicrafts and wage-earning

elsewhere? What consequences would any incompatibility between crops or between entire sub-systems have on the choice of cropping pattern under irrigation and on the farm lay-out? What other crops or activity would need a parallel intensification programme to 'make room' for irrigated cropping' What other programmes are needed to cover those aspects that have a specific bearing on lasting, self-sustained adoption of irrigation? What institutions should be developed simultaneously to support the farmers in their new farming system?

All these questions are rarely, or if so, inadequately, taken into account in the design of irrigation projects.

Discussion of the factors involved

The introduction of irrigation means one of the following:

a It converts an existing cropping system, or part of it, into irrigated cropping. Examples are the introduction of irrigation and drainage to eliminate the risks of traditional rain- and flood-dependent rice cultivation in the 'inland swamps' in Sierra Leone, or the same for flood-recession cropping along the Senegal and Niger Rivers.

b It adds irrigated cropping as a new sub-system to an existing farming system. An example is the reclamation of swampy wasteland along the shore of Lake Victoria and the allotment of irrigable plots to neighbouring farmers.

c It replaces an entire rain-dependent farming system by an irrigated farming system. Examples are the irrigated (re)settlement projects in areas where rain-fed arable cropping is marginal or not possible, as in the Gezira Scheme in Sudan and the Bura Scheme in Kenya.

Farmers will in general encounter fewer adaptation problems under *a* than under *b* and *c*, as *a* constitutes a real improvement in the existing system rather than a change.

The constraints to the successful introduction of irrigation – which means an introduction that leads to a lasting, self-sustained adoption of irrigation into new balanced farming systems – are sometimes due to deficient physical and technical planning, as was the case with the Office du Niger in Mali (de WILDE 1967). Usually, how-

(above)
In one photograph, five subsystems of a farming system commonly found in Java, Indonesia:

1. Paddy field cropping of rice with secondary crops, the main production activity of the system (in the photo, between two crop cycles);
2. Livestock keeping. By grazing the rice stubble and the bunds, the water buffaloes keep weed growth under control. Further, they produce organic manure and provide traction power for the heavy work of preparing the land;
3. Duck raising. The ducks keep down the noxious micro-fauna in the paddy fields by feeding on larvae, snails, and so on;
4. Homeyard cropping (in the background), usually with a wide variety of annual and perennial crops in mixed stands to provide the family the whole year round with products for home consumption and petty trading;
5. Household and family care (in the top left-hand corner), one of the consumptive sub-systems. Here, the dehusking of rough paddy.

ever, the true constraints are found among the following factors:
culture and tradition, felt needs, skills and knowledge, land tenure, land area, land suitability, water, climate, human health, labour, means, market, crop health, risks.

Culture and tradition

Rain-fed farming is essentially an individual family affair, with traditional forms of cooperation remaining restricted within the family in its widest sense (JURION and HENRY 1969).

But irrigated farming is typically a community affair. In smallholders' farming it would indeed be an absurdity for each family to have its own intake works and supply canals, although such inefficient situations do exist. In the western coastal plains of Madagascar, for instance, temporary transmigrants, originating from different village communities in the overpopulated highlands, run individually-irrigated rice farms for the duration of their working life – without seeking cooperation with their neighbours. Development efforts to reorganize the water distribution did not meet any particular problems once the farmers had agreed that ancestral rivalry between their native villages did not necessarily preclude the possibility of applying the traditional form of effective communal water management – which they all knew very well from their native villages.

Farmers who depend on the same irrigation system have to adopt a strict group discipline in cropping pattern (different crops have different irrigation and drainage requirements), farm operations calendar, water use, and canal maintenance. The necessary communal sense must be built up, utilizing whatever useful forms of traditional cooperative village structures there may be.

Regular farm maintenance is in itself a novelty, entirely alien to the old rain-dependent system in which a new piece of land was opened up whenever the old land was no longer arable (mainly) because of weed accumulation. Even now, in areas where shifting cultivation is no longer possible because of the shortage of land, maintenance is a difficult development theme, whether it concerns keeping the fields clean of noxious weeds, the seasonal reshaping of bunds and field ditches, or the regular repair of the homestead.

Indicative of the viability prospects of smallholders' irrigation is the active involvement of the beneficiary farmers in the construction of the irrigation works, including its work organization (BALBO 1975). Such 'human investment' in communal labour fosters group responsibility for the work accomplished, a prerequisite to motivating villagers to take part in the operation and maintenance of 'their' scheme.

Another strategy, sometimes advocated by planners as an easier and more efficient alternative, consists of getting all the construction work down to farm level done by contractors and – to make the farmers as yet feel that the scheme is theirs – by 'selling' the irrigation facilities to them afterwards through a long-term repayment contract. This strategy, however, cannot be but a faulty one: firstly, it saddles farmers with a heavy debt burden which is a poor start anyway; secondly, it does not stimulate the necessary group spirit as the farmers remain individual debtors; and, thirdly, it does not create the feeling that the scheme becomes 'theirs' as farmers normally regard such long-term financial obligations as just another government tax that skims the cream off their income (the factor *means*).

Active involvement of the farmers as from the planning stage, properly guided by purposive community development programmes, also creates the foundations for sound grassroot farmers' cooperatives, which should be able to look after the farmers' own interests – unlike the conventional 'cooperative' that is normally little else than a village-level tentacle of a neo-colonial marketing organization.

Furthermore, because of the usually high investment costs involved, irrigation planners have to work under the pressure of economic criteria. This invariably leads to simple farm lay-outs with concentration on cash crop production. Applied to the traditional farming system of the West African Sudan Zone, the irrigation scheme would take the place of cropping system 2, the cash crop 'farms' of individual villagers, mostly men. It is obvious that such a biased point of departure already encourages further individualism rather than building up the necessary community responsibility.

Felt needs

Irrigation schemes that represent the one-sided improvement or addition of one single sub-system entail almost automatically an unfair competition with the traditional family sub-systems outside the scheme. Western thinking in terms of purely economic maximization criteria tends to ignore the value of those other sub-systems even if they are an essential part of the people's living pattern. The pressure of short-term economic feasibility leaves no space in rural development design for such family and community needs as the inclusion of 'minor' subsistence crops, easily cultivable 'old people's' crops, special 'women's fields', livestock as an integrated part of the system, production opportunity for petty trading, crops that are suitable for small-scale processing industries to provide off-farm employment, and last but not least the ownership of the land.
Yet, compliance with such felt needs – which largely find their roots in culture and tradition and are important in minimizing the factor risks – might greatly contribute to the balance, hence the viability, of the new farming system, even if seemingly irrational or affecting the project's internal rate of return. It would also positively influence the people's willingness to participate in the construction and functioning of the irrigation scheme.
The basic issue therefore is whether development agencies attach more importance to long-term than to short-term project results and are prepared to set project-appraisal criteria accordingly. If so, they will consider not only the factors water, land, and climate but, in choosing the cropping pattern, they will also consider the farmers' felt needs, the labour required for the crops, and the long-term cost returns expectations (the factor means). On this basis they will decide which compromise solution is preferable: a farming-system development project with irrigated as well as rain-fed cropping and other sub-programmes, or solely an irrigation project but then designed for a widely diversified cropping pattern which requires, undoubtedly, a more complicated scheme lay-out.
The latter option is virtually a must in semi-arid and arid areas where non-irrigated cropping is too marginal or not possible at all. There, because of the different requirements placed on irrigation and drainage by different crops, each holding should have as many plots as it will have crops or crop mixtures and fallows (if these are necessary) in any one season, with each plot located in a different irrigation unit ('quaternary unit'). This has direct consequences for the size and shape of the tertiary and quaternary units and for the size and location of the villages, because the distances between the plots of a single holding as well as between the fields and the village should be as short as possible.

Skills and knowledge

In areas where irrigation is not a traditional prac-

Farmers do not like to depend on cash crop production alone, in their irrigated plot they want to grow food crops as well. Here, 'illegal' maize and beans (in the foreground of the photo) in an irrigation scheme in Kenya.

tice, people do not know how to operate the water supply, how to dose the quantities of water, what the specific crop requirements are for both irrigation and drainage, how to prepare the land, or how to repair bunds and canals. They do not realize the dangers of water-borne diseases or the effects of agro-chemical pollution on human health. They do not know how to avoid erosion and salinization of the land. They are ignorant of the effect on crop health of prolonged waterlogging, insufficient weed control on bunds and road sides, and the overlapping of standing crops that cause the accumulation over the years of pests and diseases, a very common cause of declining yields.

This all calls for intensive farmer training (Extension) even more highly geared than that required for the introduction of a new crop in rain-fed farming. At least during the take-off phase of the scheme, this training should be guided by operational extension research to develop locally adapted extension methods and explore particular adoption problems.

Intensive farmer training, however, will remain an academic proposition only, unless qualified local staff is available to do it. Here, we touch upon a basic problem of the Third World countries; and the shortage of qualified staff specialized in irrigation is particularly pronounced. In most countries where irrigation is a novelty, the formal educational facilities to specialize in irrigation do not even exist. The system of strict management control in many of the larger irrigation schemes has without doubt been the answer to the problem of how to realize high investment returns within a short time and with an absolute minimum of staff qualified in irrigation matters. The question then remains: what is being done to improve the man-power situation in those countries where, from senior staff down to farmer level, skills and knowledge are apparently the major constraint for irrigation ever to become an integral part of a balanced smallholders' farming system?

In fact, very little is being done. 'Counterpart' training, although stipulated in almost every project plan of operation, has proved to be a myth. And badly needed development efforts to assist local universities and lower training institutions in setting up formal irrigation courses are rare.

If national and donor development agencies could agree that 'development primarily concerns *people*', and also agreed that 'development will result from a build-up of people's knowledge of their natural environment and its possibilities', they would give man-power training the highest priority in development cooperation. The results of irrigation projects would then not primarily be evaluated, as now, on the basis of short-term production successes – which has proved in practice to be an *'après nous le déluge'* approach, leaving the host country with the problems of follow-up and continuity – but on the basis of the number and competence of staff trained by the projects and of actual community performance by the farmers.

Irrigation projects should be designed accordingly, with emphasis on the training component. In-service training should have a systematic, organized character, geared to produce several qualified nationals per (only temporarily assigned) 'expert' – several, to allow for drop-outs and yet permit project expansion. In view of the increasing staff requirements in the future, the project plan should also include that project staff lecture part-time at existing training institutions, that they supervise and guide temporary project-based students, organize courses for non-project personnel, and conduct workshops for senior staff of relevant government services, universities, and research stations.

Land tenure

Often forming a serious constraint to irrigation development are the old land ownership or traditional land use rights. These should be studied and the solutions definitively accepted by all parties concerned prior to project implementation. Otherwise, problems may arise from people harassing scheme farmers, under the pretext of having older land use rights; or, especially in riverain areas, which were of old the dry-season grazing grounds of pastoralists and have since been reclaimed and converted into irrigated land, from transhumance livestock herds that seasonally inflict damage to crops and irrigation infrastructure. As disciplinary measures to keep the pastoralists out may seriously upset their traditional livestock system, the only acceptable solution in this case would be to consider the introduction of irrigated agriculture in a broader context of 'area development', with two parallel but interrelated development programmes, one for irrigation development and the other for livestock intensification.

Another problem related to land tenure is that irrigated cropping implies permanent land use. This has consequences for the most desirable tenure status of the scheme farmers because permanent and intensive land use requires regular investment (allocation of means) on the part of the cultivator. The necessary motivation to invest, however, is certainly not fostered by the common practice in large irrigation schemes of granting to scheme farmers the permanent status of *tenants* only. Scheme farmers should have a title-deed to their irrigated plots, provided, of course, that strict regulations protect them from the dangers of mortgaging their land to money-lenders and middle-men once the irrigated land has become a marketable property.

Land area

The total area of irrigated land to be allocated to each holding is usually decided on the basis of the estimated labour requirements of the crops that are to be grown in the scheme. No consideration, or only very little, is given to the labour required for other family activities or to the quite conceivable possibility of having to grow other crops because of market or other constraints. Moreover, labour requirements are often underestimated. For instance, rice transplanting in most African rice schemes turns out to require about twice as much labour as it does in Indonesia. If the labour-requirement calendars of the various sub-systems prove to be incompatible, the farmer will be forced to neglect one or more of the sub-systems. Depending on what activity responds best to his felt needs, he will not infrequently neglect his irrigated crop(s); the result is yields below expectation – as happened, for instance, in the rice schemes in Western Kenya that were added to an existing farming system with year-round activities. Sometimes the off-scheme activities tend to be neglected – thereby increasing the farmers' risks – as happened, for instance, in the otherwise successful village rice schemes along the Senegal River.

If the planners had had a thorough knowledge of the existing farming system in all its facets, if they had made a less generous allocation of irrigated land per holding, and had instituted a polyvalent action programme, a more balanced development would probably have resulted. In the Western Kenya rice schemes, where four-acre plots were allocated to surrounding farmers, smaller plots of, say, half an acre or one acre each would not only have enabled farmers to devote more care to the crop and thus obtain higher yields, but it would also have given four to eight times as many poor families in the area the opportunity of improving their income.

Land suitability

In its cropping potential and possibilities for irrigation, land suitability is not a fixed qualification. It is subject to change when the land is used for agricultural production (MOORMANN and van BREEMEN 1978). For instance, soils that were once classified as permeable and therefore less suited for wet-rice production may lose their permeability after some years of cultivation and become good padisoils but less suitable for the originally planned 'dry-foot' crops. Or soils may lose their originally assessed fertility level – the basis of the feasibility expectations – because of the high export of soil nutrients and the incomplete replenishment by a one-sided fertilizer that was once considered adequate. Other changes in soil characteristics may be due to salinization or to wind or water erosion of the topsoil. All those changes in land suitability, with the risk of reaching the point of no return, can be put down not only to inadequate input of labour and means, but also, if not in the first place, to insufficient knowledge of the appropriate agricultural practices. Intensive land use, made possible by irrigation,

Ancient method of lifting water for the irrigation of thirsty land in the Augila Oasis in Libya. A simple, modern improvement was to line the conveyance ditches with plastic to reduce the water losses in the sandy soils, thereby greatly shortening the time required for the twice-daily watering of the tiny plots of wheat and tomatoes. Note the screens of date palm leaves along the tow path to protect man and mule from the blazing sun.

should be accompanied by on-farm research of the 'monitoring' type to keep the scheme management knowledgeable of the processes of change set going by the development intervention. Soil monitoring, unfortunately, is seldom done in practice, although it can be a relatively simple matter: selected farmers can be trained to do regular soil sampling and/or cooperate in conducting observation plots. Monitoring should be part of a routine after-care of the project, to enable scheme management and extension workers to take timely corrective measures and to adapt the extension themes whenever necessary.

Water

Poor irrigation and drainage are a very common cause of disappointing crop yields. The basic problems may lie in the factor skills and knowledge (also on scheme level) and in the attitude towards maintenance (culture and tradition). But it is no exception either that a drainage network is simply excluded from the scheme lay-out because of considerations of keeping the investment costs low: an economic short-sightedness that leaves the farmers and the host country in the lurch after some years of cultivation.

Poor irrigation and drainage may also be due to poor land preparation, especially levelling, resulting in spots with water shortage, which encourages noxious weed growth, and spots with excess water, which hampers tillering or causes asphyxiation.

Gradual yield decline due to insufficient water control is often caused by too tight a cropping pattern, which leaves no time for the periodic drying of the soil. Prolonged waterlogging leads to severe soil reduction, which – depending on soil type, pH, organic matter content, and other soil characteristics – promotes a range of physiological diseases and thus affects crop health. Some of these diseases are known to be related to an excess of soluble ferrous iron, sulfides, or organic acids, or to a lack of zinc (MOORMANN and van BREEMEN 1978).

Insufficient drainage and/or under-irrigation may also cause a gradual salinization of the soil, with a resultant decline in land suitability. A classic example is the deterioration of ancient irrigated agriculture in the Middle East.

Climate

The climate is one of the decisive factors in the planning stage of an irrigation scheme, affecting, as it does, the scala of suitable crops and the design of the irrigation and drainage network. Once the scheme is there, however, a true climate constraint is the irregularity of the rainfall pattern. An irregular rainfall pattern makes it difficult to ensure the proper control of water, especially in large irrigation schemes with poor communications between the tertiary unit and the main and secondary water-intake works. In such schemes, it frequently happens, during the usually very erratic rainy seasons, that large quantities of expensive irrigation water are wasted or, if kept on the fields, cause flooding and subsequent crop damage.

This problem could largely be overcome by setting up a warning system to report the mostly very local rainstorms to the operators of the intake works. The farmers themselves could play a major role; grouped per tertiary unit, they could elect a 'water guard' who, after appropriate training, would assume responsibility for immediate rainstorm reporting and for the operation of the tertiary water-intake and drainage gates. This water guard should be a 'community official' and should receive from his farmers' group an incentive in the form of a nominal monthly fee, perhaps partly in cash and partly in kind.

Human health

The factor human health deserves special mention because the introduction of irrigation into an area may thoroughly upset the local parasitic ecosystems and, by so doing, cause an explosive development of water-borne diseases. Particularly notorious are river blindness, whose vector, the *Simuleum* fly, breeds in running water, and the diseases whose vectors breed in standing water: malaria (transmitted by *Anopheles* mosquitoes), and bilharziasis (spread via *Bulenus* snails). These and other (e.g. intestinal) diseases seriously affect people's health, and hence their labour, and by that jeopardize yields and income (the factor means).

Any plan to introduce irrigation should therefore include: in-depth inventorization of indigenous diseases and their vectors, and in the case of resettlement projects the same in the areas of settlers' origin, to be followed by regular vector control campaigns and preventive routine health care.

LUCASSE (1976) suggests that traditional healing arts be given new impulses for development by integration with simple western methods, and that local medicine should play an important role in routine health care after the phasing-out of the project.

Adverse effects on labour and ultimately on means are also caused by seasonal food shortages or chronic malnutrition. One-sided project orientation to develop cash crop production cannot but aggravate, if not induce, such problems.

Labour

The various smallholder activities all draw from the same farm family labour resources, supplemented for certain farm operations by neighbour help, casual wage-labour, and animal power. The introduction of irrigation will necessitate an important shift in the traditional allocation of labour because of the specific labour requirements of irrigated farming. These concern not only a more intensive level of crop cultivation to make optimum use of the high production potential offered by the irrigation facilities, but also concern community constraints of a strict farm operations calendar and of the additional communal work load required for the regular maintenance of bunds and canals. The community aspects have already been mentioned under culture and tradition, the competition for labour between the different sub-systems under land area per holding, and the influence of health and nutrition on working ability under human health. Working motivation on the other hand is mainly a question of priority ranking of felt needs and of the expected return on efforts (the factor means).

The many unknowns that determine farmers' behaviour as to labour allocation, ability, and motivation – which, moreover, will differ from project to project – cannot be solved during a project's planning phase. They therefore require a flexible project design with an important socio-economic research component of the monitoring type. This will permit timely programme modification, adjustment of the cropping pattern, or any other improvement measure, according as research data become available.

Means

Development is usually measured on the basis of estimated net income, a rather dubious criterion as is illustrated by the Gezira Scheme, where the situation of the farmers does not reflect the Scheme's reputation of success: 'Those farmers who are solely dependent on their tenancy (the majority of the tenants) are in a situation of constant indebtedness and shortage of cash' (BARNETT 1979).

This is, in fact, a very common situation – found in many production intensification projects and not only in irrigation schemes. Causes may be manifold, their main points differing according to project type and to natural, cultural, and institutional conditions. Many of them, however, share the following shortcomings:

- Farmers are not credit-minded, in the sense that they do not fully realize the consequences of a debt burden; they tend to take up credit rather injudiciously; for instance, they expend their means to hire labour or tractor services for work that could well be managed by themselves and their family, or to buy luxury goods and foods. This can be explained by influences from the environment (induced felt needs) and ignorance (the factor knowledge). Credit should be a principal extension theme in development work, which in practice it seldom is

- Reliable credit facilities are inadequate, either in volume or in flexibility or are meant (the usual case) for a single cash crop only, which drives farmers into the hands of profiteering moneylenders. Credit facilities should be developed to cover the requirements of the farming system as a whole. Part of the credit, e.g. for consumptive use, might better become a community responsibility ('Village Funds')
- The farming system is not balanced. Farmers are not self-reliant in food production, because of too narrow a cropping pattern imposed on them by scheme regulations; they are obliged to purchase their food for much higher prices than it would cost them in home-production. Especially in the months prior to food crop harvest, market prices for foodstuffs may reach exorbitant levels, which are not reckoned with in the original net income estimates
- Market outlets or prices for the cash crops are not guaranteed, as will be discussed in the next section.

Market

The construction of an irrigation scheme, with its high production potential, within a region that otherwise remains dependent on the whims of natural rainfall, may cause the collapse of the local markets for the irrigated commodity and wipe out its traditional producers outside the scheme. Examples can be found in West Africa (irrigated vegetable production) and India (isolated irrigated rice schemes).

Irrigation schemes should therefore be part of a regional development plan, with parallel development programmes and appropriate market-protection measures for the farming communities outside the schemes. Programmes inside and outside the scheme should complement one another.

Examples exist also of irrigation schemes where the obligatory market crops do not find a guaranteed post-harvest outlet when needed; for instance, outgrowers' sugarcane that has to wait. until the nucleus estate's production has entered the processing line. Examples are also known of the (again) obligatory cash crops being subject to strong and irregular price fluctuations because of unpredictable production levels elsewhere.

In such cases, the risks of market production are shifted entirely onto the shoulders of the intended scheme 'beneficiaries', who have no reserves to make up for even occasional losses. Firm marketing guarantees, flexibility in the cropping pattern, and the build-up of farmers' cooperatives, able to protect individual and group interests, form the essential pre-conditions for irrigated cash crop production.

Finally, certain market aspects such as price ratios between inputs and expected outputs and the reliability of timely input supplies are so well known that they need no special discussion. Suffice it to say that they exert a predominant influence on farmers' motivation and, ultimately, on farmers' income (means).

Crop health

Necessary for sound crop yields, crop health, in respect to both its nutritional status and freedom from pests and diseases, is the combined result of various factors that have already been discussed: skills and knowledge of correct agricultural practices, land suitability, proper water control, climate, sufficient and timely labour inputs, and the necessary expenditure of means for adequate crop protection and plant nutrition.

These very factors, however, give rise to as many constraints – constraints that are difficult to control, especially for the small farmer. The growing awareness of this fact and the increasing concern on national and international levels about the problems that small farmers face in adopting modern technology, has in recent years led to a reorientation of research towards new technology that fits better within the framework of possibil-

Mixed cropping – here in a homeyard in the Selva Zone of Peru – has many advantages: it makes optimum use of (limited) land, water, and light; it saves labour, keeps down pests and diseases, protects the soil by a permanent vegetative cover; and last but not least, because of the variety of crops grown throughout the year, it provides the farmer with some degree of protection from the risks of individual crop failures.
Western prejudice against mixed cropping, because of the difficulties it poses for mechanization, was the reason why the possible improvement of this cultivation method was so long neglected by researchers.

ities of the small farmer 'as he is'.
Especially in areas where irrigation is not traditional, for instance, the variety choice of the irrigated crops should be based rather on considerations of obtaining satisfactory but stable yields even under adverse conditions than on high-tuned expectations of super yields that require perfect growing conditions and high input levels. In a later project-phase, more exacting extension themes, including the use of modern varieties and increased input levels, can always be introduced when farmers have reached the necessary farm management level to adopt such themes profitably.

Risks

It is probably their strategy of risk-avoidance that characterizes all small farmers. The world over and whether commercialized or not, traditional farming systems have evolved which have given proof of real viability – something that obviously cannot yet be said about the modern, (meant to be) improved farming systems designed *for* small farmers (but *without* them) during the last decades of development cooperation efforts.
Although irrigated crop production in itself is less risky than rain-fed farming – and is the reason why farmers normally show great interest in irrigation – the very dependent status of the tenant-farmers *vis-à-vis* the scheme management with regard to water supply and, in many schemes, also the timely arrival of machinery and inputs, implies great risks for them.
Just imagine what would happen if, in an isolated irrigation scheme with a narrow alternating cropping system of cotton followed by maize (the planned cropping system for the Bura Scheme, Kenya), water supplies were to break down during maize flowering and this sole food crop fails. The result would be soaring market prices for foodstuffs and indebtedness of the tenants to money-lenders and middle-men.
Also the farmers' dependence on one single cash crop, which gives them a bulk cash income once a year, bears great risks for them: either because of possible crop failure or – a very common thing – because of injudicious spending after pay-out due to ignorance (the factor knowledge) and the appeal of western luxury goods (the factor felt needs) induced by commercial pushing ('Guinness is Good for You!') through uncontrolled market interference.
Diversity of production sub-systems as well as of crops within cropping systems has always been a very effective way of reducing risks in traditional farming systems (UPTON 1973). It appears that diversification also remains the best solution for low-risk irrigation development. To this should be added the important agronomic consideration that crop diversification and a judiciously designed crop rotation permit optimum utilization of family labour resources throughout the year, and are, of old, the cheapest way of maintaining soil fertility.

Conclusions

Within the sphere of salient factors discussed above, the farmer is expected to take his best farm management decisions. To state that the introduction of irrigation is complicated and involves more than merely digging canals and deducting the costs from crop proceeds is obviously forcing an open door. But the question remains: what development strategy should be adopted to assist farmers to integrate irrigation into a new balanced farming system? Fundamental for such a strategy will be:

- To place basic farm management responsibilities in the hands of the farmers themselves. There is no indication whatsoever in the history of development intervention that a take-over of those responsibilities by outsiders can result in *lasting, self-sustaining agricultural development*. The role of scheme management should be restricted to guiding the farmers in their technological and socio-economic development process, providing services and technical facilities on the basis of a policy of decreasing scheme management decision and maximum delegation, thereby evoking among the farmers the maximum of initiative and responsibility. The farmers' way of life, their group identity and personal dignity are the only legitimate objects of development efforts (BUNTING ed. 1970)
- To adapt project design and technology to the farmers' needs and possibilities, building on the basis of the existing farming system. This requires a thorough study of the local farming system and all its sub-systems, to be followed during project implementation by 'Farming Systems Development Research' (CGIAR 1978). Essential in this type of research are on-farm testing and monitoring
- To plan project programmes according to *constraints priority*, so as to make the project design no more complicated than need be. This requires flexibility in the original project design. It also requires, as a component of the farming system research, 'constraints research' of the type developed by the International Rice Research Institute, Los Baños, Philippines (DE DATTA et al. 1978)
- To involve the intended beneficiary farmers in *scheme affairs* as from the planning stage, promoting community work and the formation of farmers' associations based on communal interests, and training them from the very beginning to gradually take over the responsibilities of tertiary unit (or village scheme) operation and maintenance
- To assure, within a regional development context, the build-up of, and communication between, farmers' associations, research, extension, input supply, credit, a fair and stable market and other services. Appropriate in-service as well as formal training is a prerequisite for such 'institution-building', which should be an essential element in any irrigation development plan.

These five principles should be pursued simultaneously. This has several consequences for development policy-making, first and foremost of which is a reconsideration of current techno-economic project appraisal criteria that have proved to be of little relevance for the long-term viability of irrigation schemes. Secondly, the complexity of irrigation development demands a programmatic, well-coordinated, multi-sector approach, beginning on a modest scale ('starter projects'), so as to allow a satisfactory fanning-out of the programme as knowledge, experience, and qualified local man-power are generated. Thirdly, the complexity of irrigation development also requires that donor agencies abstain from individual, non-integrated (and in fact mere flag-showing) irrigated-production projects, but rather pool resources to enable the host country to build up its own abilities to implement the necessary long-term multi-sector programmes.

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Crop response to water under irrigated conditions

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Introduction

Before the dawn of recorded history, farmers had recognized that good water management meant higher crop yields. Early civilizations were founded on the stable food production systems that farmers had created through irrigation or other practices like controlled flooding and water conservation.

Demographers tell us that the world's population will be doubled by the year 2000. Mankind is thus facing an enormous challenge: to feed those extra mouths, it must rapidly and vastly increase its food production. Certainly, much of this challenge will be met by improving rain-fed farming systems, which account for 84 per cent of the world's total cultivated area, but irrigated agriculture will also have a great role to play.

Most of the basic and applied research in the world is conducted in the technologically advanced countries, whereas most of the world's irrigated areas are located in developing countries. As it is precisely in the latter countries that the demand for greater food production will be the most pressing, it is vital that we consider the advances made in the western world and examine the extent to which they have been, and can be, transferred to the developing countries.

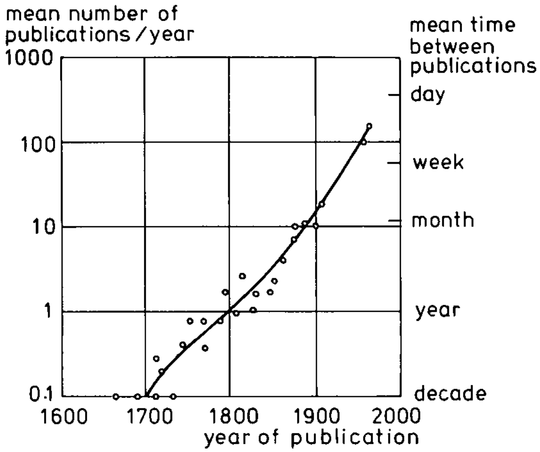
In the search for ways of raising food production under irrigation, a central theme is the study of soil-water-plant relations. These relations are the underlying principles of the effect that water has on crop yield. Many sciences are involved in working towards a better understanding of them. Indeed, research in such fields as soil physics, meteorology, and plant physiology has contributed substantially to better water management systems and to more stable cropping systems. Traditionally, most of the research into the relationships of soil, water, and plant has been directed towards cash crops such as cotton, hybrid maize, and sorghum. And much of that research has concentrated on optimizing the factor 'water', assuming other production factors to be not limiting for crop production. But to what extent are the advances made in such research of practical value under conditions where these other factors are indeed limiting? Let us examine the issue.

A crop's response to water is closely related to the amount of water used by the crop. We shall therefore first turn our attention to the subject of crop water use and discuss the progress made in this field. We shall then turn to our main subject, i.e. the effect of water on crop yield, and follow it with examples in practice. Finally, we shall attempt to predict the developments that may take place in times to come.

Crop water use

At the beginning of this century, researchers were

Figure 1.
Growth of meteorological literature on crop water use since 1670. Mean annual number of publications per decade (STANHILL 1973a).



showing particular interest in the relation between the water use of a crop (transpiration) and the crop's dry matter yield, expressed as transpiration or water use efficiency (kg.kg.$^{-1}$). Many attempts were made to determine the ratio between the two. De WIT (1958) re-analyzed some of these studies and explained much of the observed variations in this ratio.

In the last decades, the interest being taken in crop water use has grown enormously. STANHILL (1973a) estimated that literature on the subject exceeded 18,000 items. Of this total, about one quarter is meteorological literature, i.e. studies on the relationship between weather factors and crop water use. Figure 1 illustrates the prodigious growth of this literature since 1670. Stanhill also estimated that during the mid-1960s the annual cost of studies on crop water use was of the order of 10 million dollars. His figures refer only to the research reported in international literature. They thus leave out of account the research being conducted in developing countries, because few of these reports are easily accessible.

So 18,000 items of literature is probably a very conservative estimate. And if we consider the highly sophisticated tools now being used in crop water research, we can probably conclude that the current annual costs are several times Stanhill's estimate.

A large majority of the work reported concerns methods with which to estimate 'potential evapotranspiration', i.e. the maximum amount of water a crop can transpire. Almost all these methods use one or more meteorological parameters, and most of them are empirical (e.g. Blaney-Criddle, Thornthwaite, Turc, and pan evaporation methods). As they need to be calibrated locally, they have only limited applicability.

The main difficulty in using the above methods is the need for crop coefficients with which to convert an estimate of open water evaporation to potential evapotranspiration of a given crop. Many field trials have been, and are being, conducted to measure the potential evapotranspiration and then to relate the measured values to meteorological parameters or functions thereof. Publications by JENSEN (1973) and DOORENBOS and PRUITT (1977) compile experiences from many of these trials and present modifications of some of the more widely used methods, including recommended crop factors for each method.

For the accuracy required in feasibility studies and for project design and operation, the current methods of estimating potential evapotranspiration would seem to be adequate, although for day-to-day irrigation scheduling, local calibration is still required.

From a scientific viewpoint, only two important developments have contributed to a better knowledge of evaporation theory: the work of PENMAN (1948) on the combined heat-balance/mass-transfer equation and the eddy correlation method of SWINBANK (1951).

Typical of all that work on crop water use is its orientation towards maximum crop yields and its concentration on cash crops. The underlying philosophy was that one should aim at maximum crop yields per unit of land. Over the last ten years, a shift away from that philosophy has become apparent. The realization that supplies of good quality water are limited and that these supplies are also being competed for by industry and domestic users has been calling for a more efficient use of irrigation water. Considerations of energy costs and capital investments are also involved. As a result, 'deficit irrigation' has come to be accepted in many circumstances. It has been found that optimum crop yields can still be obtained even though the crop 'suffers' from water shortages during certain stages of its growth. Withholding water during these stages obviously decreases the crop water use.

An example of how evapotranspiration drops with longer irrigation intervals is shown in Figure 2. (The crop is cotton on a fine-textured soil in Egypt).

As can be seen, for some time after irrigation the crop transpires at the maximum rate and then, as the soil dries out, this rate drops. Whether a reduced rate of evapotranspiration is permissible depends on the effect such reduction would have on the crop.

Accompanying the acceptance of deficit irrigation is the growing interest in the development of practical methods of estimating 'actual evapotranspiration', i.e. crop water use under limiting water availability. Important research in this field has been reported by RIJTEMA (1965), MONTEITH (1965), and RIJTEMA and ABOUKHALED (1975). Some of this research takes the form of establishing production functions, i.e. of indicating how crop yield varies with changing water availability; some researchers use models to describe this relationship.

Better instrumentation (thermocouple psychrometer, porometer, neutronmeter, etc.) is enabling more accurate measurements of the soil-water-plant status and its interactions, which can then be described mathematically and generalized for broader application. A new avenue is being opened by the use of remote sensing techniques. With 'traditional' instrumentation, it had previously been difficult to determine surface temperatures, but remote sensing techniques are now overcoming this problem.

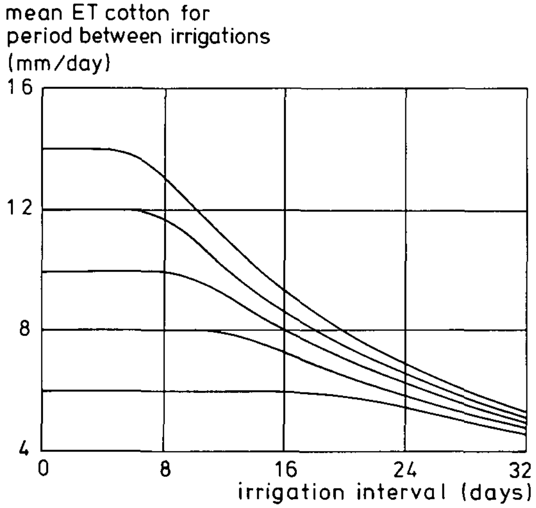


Figure 2.
Mean actual ET cotton over the irrigation interval for different durations of irrigation interval and for different ET cotton levels (RIJTEMA and ABOUKHALED 1975).

Modelling the effect of water on crop yield

With the 'rediscovered' importance of the effect of water availability on crop yield and the great complexity of the relation between the two, sophisticated models have been developed, ranging from statistical models to crop growth simulation models. But, as in many other sciences, people are now returning to more simplified methods. This is especially true for applications in developing countries where the detailed data for complicated models are lacking. In the meantime, however, the use of complicated models has contributed much to the improvement of simpler models.

In discussing the different approaches followed in assessing relationships between crop water use and crop yield, it is convenient to divide them into three groups:

- simplified agroclimatic indices
- crop-weather models, and
- simplified crop-water-use/yield models

Simplified agroclimatic indices

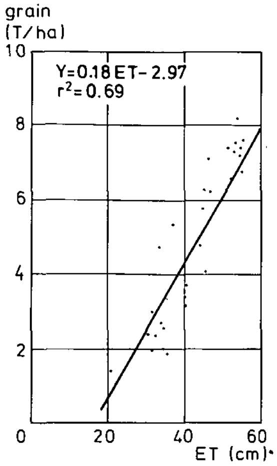
It has always been difficult to describe exactly how water affects crop yield. Research has therefore been seeking one factor (or a combination of a few factors) that has some relationship with water availability. Such a factor is then called an index. The most simple index of water availability would be seasonal rainfall (or rainfall plus water supplied under irrigation). However, the relation between rainfall and crop yield varies from year to year and depends on the distribution over the season. Another index therefore had to be sought. A convenient one, and one often used, is evapotranspiration (the amount of water used by a crop).

Evapotranspiration provides an agroclimatic index which, apart from integrating soil characteristics as is done when soil water status is used as an index, also includes the effect of plant factors. Evapotranspiration is thus widely used for assessing the effect of water supply on crop growth and yield.

STANHILL (1973b) presented a review of studies and methods in which evapotranspiration, in some form, is used as an index. Some more recent examples are briefly described here.

For a number of crops and conditions a close linear relationship has been found between actual evapotranspiration (ET) and crop yield. An example, adapted from HANKS et al. (1978) is shown in Figures 3 and 4 for corn grain yield and corn dry matter yield, where r = correlation coefficient.

There is increasing evidence, both theoretical and practical, that such linear relationships need to be



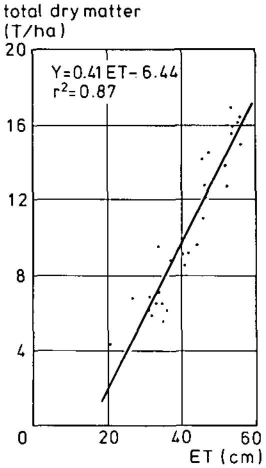


Figure 3.
Corn grain yield in 1975 (15.5% moisture) as related to evapotranspiration at Logan.

Figure 4.
Corn total dry matter yields in 1975 as related to evapotranspiration at Logan.

modified to allow transfer to climatologically different areas, and also that growth stages in crop development need to be taken into account when relating evapotranspiration to yield.

A simple but illustrative example of how the timing of irrigation and the quantity of water applied affects crop yield is shown in Figure 5.

The data originate from an irrigated wheat trial at the Texas Agricultural Experiment Station. The only variant between treatments of one to four irrigations of uniform depth was their application at different stages of growth. All these stages fall within a period in which wheat is known to be critical to available water. It is seen that at the same level of crop water use the yield may vary as much as 30 per cent, depending on the timing of water application.

Studies in Canada, U.S.A., and Australia in the late sixties showed the usefulness of using the ratio of actual to potential evapotranspiration at defined growth stages as an index of crop yield. A nice example of this approach is given by NIX and FITZPATRICK (1969), who obtained even better results by using a 'stress index' consisting of the estimated available water (mm) at the beginning of the critical flowering stage divided by the mean potential evapotranspiration rate during the critical period. (mm.week^{-1}). Figure 6 shows such a relationship.

A comparable approach was followed by Hagan and associates (see e.g. STEWART et al. 1973). Some of their results are shown in Figure 7, where variation from year to year is taken into account by using evapotranspiration and yield *reductions*.

The effect of growth stages is introduced by breaking the spectrum of results into zones representing different ranges of yield reduction ratios as expressed by the percentage of yield reduction divided by the percentage of ET reduction. Zones are then found to be the result of different evapotranspiration sequences, i.e. the regime of optimum or suboptimum water availability throughout the growing season. These are just a few examples of the numerous approaches to using simple expressions of evapotranspiration as an index of the effect of water supply on crop yield. Such relatively simple agroclimatic indices have proved to be of value provided they are locally calibrated.

Crop-weather models

Crop production is generally determined by the prevailing environmental conditions, i.e. by the existing complex of physical, chemical, and biological factors. Considerable progress has been made in recent years in quantitatively expressing plant performance by a function that integrates the many variables that comprise the environment.

To obtain data suitable for such a function, one of two experimental approaches is usually followed: either experiments are conducted in con-

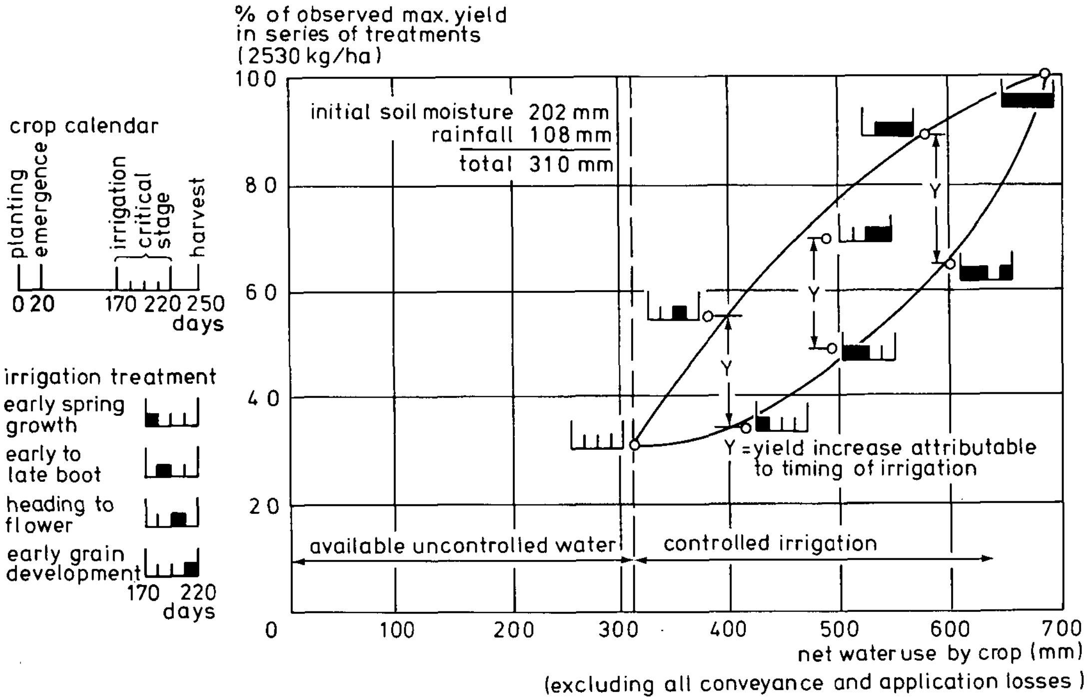


Figure 5.
The influence on wheat yield of amount and timing of irrigation.

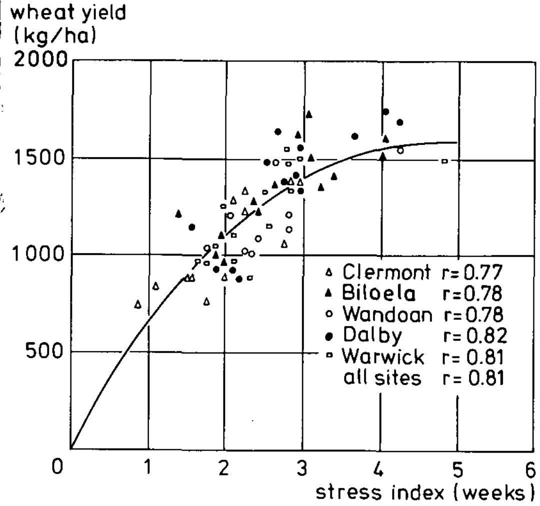


Figure 6.
Relationship between wheat yields and computed stress index at five centres in Queensland between latitudes 22 °S and 20 °S. (NIX and FITZPATRICK 1969).

trolled climates (e.g. glasshouses) where only one or a few elements are controlled according to the experimental plan; or, field experiments are conducted in which, as far as possible, all variables except weather (or water supply) are standardized.

With such limitations, it is obvious that the crop-weather relationships so obtained are difficult to apply under practical conditions where other variables will also affect crop yield.

BAIER (1979), in analyzing current crop-weather models, distinguishes between the following three types:
- crop-growth simulation models
- crop/weather-analysis models, and
- empirical statistical models

In *crop-growth simulation models*, the effect of meteorological variables on such processes as photosynthesis, transpiration, or respiration is simulated by a set of mathematical equations based either on experiments or on available knowledge. These processes are then integrated to simulate crop growth. Examples of large plant growth models are ELCROS, SPAN, and SIMED, known by their abbreviated names.

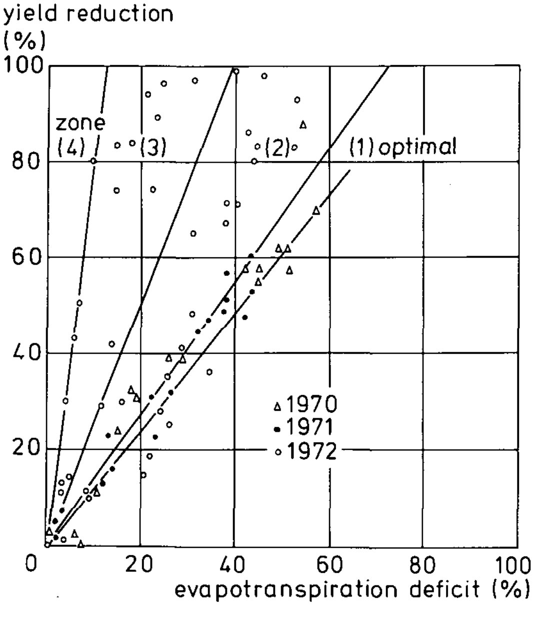


Figure 7.
Division of 3-year corn data into zones to analyse relations between ranges of yield reduction ratios and associated ET deficit sequences (STEWART et al. 1973).

The *crop/weather-analysis models* use soil moisture, evapotranspiration, or other data derived on a day-to-day basis, and relate these data to factors like crop yield. These models often incorporate a sub-model ('biological clock') to monitor the state of crop development towards maturity. An example is the model presented by BAIER (1973).

The *empirical statistical models* use yield and weather data to arrive at estimates of coefficients by some type of regression technique. Such models do not explain a cause-and-effect relationship, but are useful in relating available yield data to climatic data to evaluate historical, current, and to some extent future crop yield statistics. Examples are the regional yield prediction models for wheat, barley, and oats by WILLIAMS et al. (1975).

These three types of models can all be defined as simplified representations of the complex relations between crop performance and weather; all use established mathematical and/or statistical techniques.

Important breakthroughs in the development of models have been: potential evapotranspiration, heat units and their various modifications, soil moisture budgeting, and similar techniques that require only standard climatological data as input. This applies especially to the crop/weather-analysis models and the empirical statistical models.

With increasing fundamental research, various plant processes like photosynthesis, water flux in plant and soil, translocation, respiration, light interception etc., are now better understood. Thus the scope for integrating the descriptions of such processes into large-scale crop simulation models is expanding.

Simplified models

Apart from the simplified *indices* described earlier, simplified *models* are gaining rapidly in popularity. Their development has been possible by the advances made in process models. These simple models generally concentrate on only one practical variable and usually employ longer periods of time than those used in larger models. Examples are the model of FEDDES et al (1979), which concentrates on the effect of soil-physical aspects of water use and crop yield, and that of SLABBERS et al. (1979), which concentrates on the effect of growth stages on water-use/crop-yield relationships.

Several such models are based on the early work of de WIT (1958) and on that of BIERHUIZEN and SLATYER (1965) from which we know that water use and productivity are dependent on the supply of radiant energy and that both are influenced by plant and environmental factors that control gaseous transfer between plants and the atmosphere. By expressing these processes in mathematical equations, a correlation can be found between water use and productivity.

An important contribution to this work was made by de WIT (1965) with his computation of photosynthesis of a standard crop under standardized conditions. This computation can be used to correlate water use and productivity data from climatologically different areas.

An application of such a model is shown in Figure 8.

To determine the relative reduction in yield, the potential grain production was calculated by a linear model based on standard meteorological and agronomic data. (For details, see SLABBERS et al, 1979). The relations 1 to 4 refer to different ET deficit sequences throughout the growing season. Calibration and testing was done against data obtained under controlled conditions (experimental stations), with water as the only variable.

Simple presentations of crop response to water are given by DOORENBOS and KASSAM (1979). Further verification of such simple relationships is still required.

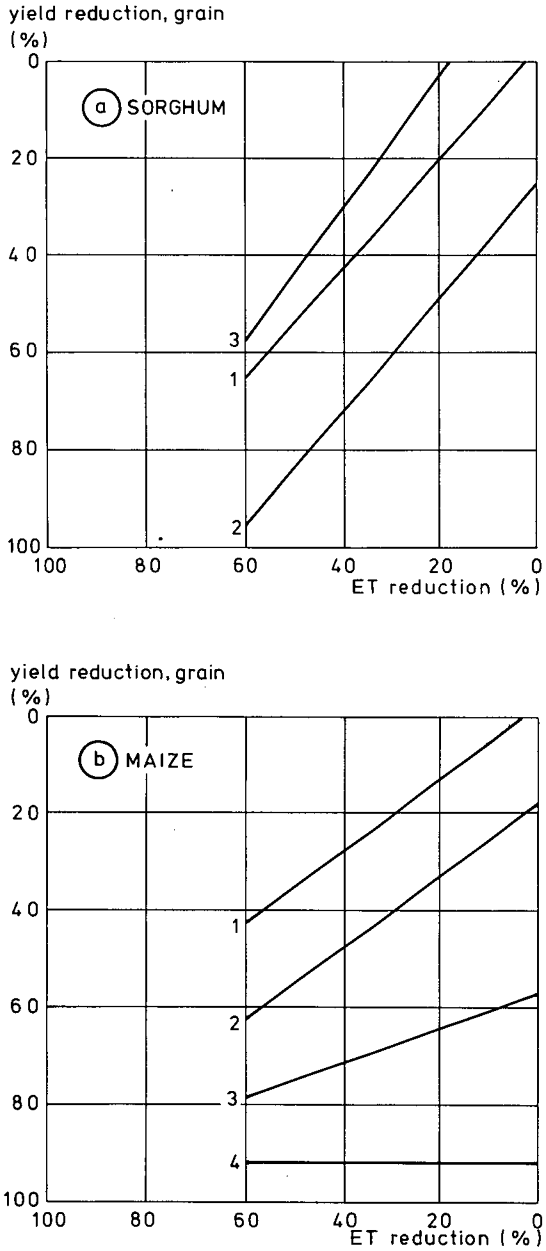


Figure 8.
Relation between reduction in evapotranspiration and reduction in grain yield for sorghums (A) (4 locations, 6 seasons) and for maize (B) (3 locations, 5 seasons) for different sequences of ET-deficits.

Applications in water management

In the U.S.A., where research has produced much accurate information on crop water use, models are being increasingly used to improve water management practices. Results from lysimeter studies, for instance, have been incorporated into computer models to estimate crop water use under prevailing and predicted weather conditions. These estimates are then fed into irrigation scheduling models. Commercial scheduling services and the Bureau of Reclamation employ scheduling procedures that use weather factors to predict when and how much to irrigate, combined with field measurements (gypsum blocks, gravimetric sampling or neutron meters) to adjust for water application and rainfall inaccuracies. Such services were used for the irrigation of more than 300,000 acres in 1976 (SPLINTER 1976). There is a growing tendency to incorporate plant growth (sub-)models in irrigation scheduling models.

For developing countries, such refined techniques of irrigation scheduling are still a utopia. There, irrigation projects are still being designed as they were several decades ago; their layout does not permit variable irrigation scheduling. Even so, there are signs that also in the developing countries work is underway to find practical production functions for irrigated crops. An example from the Philippines is reported by ROSE-

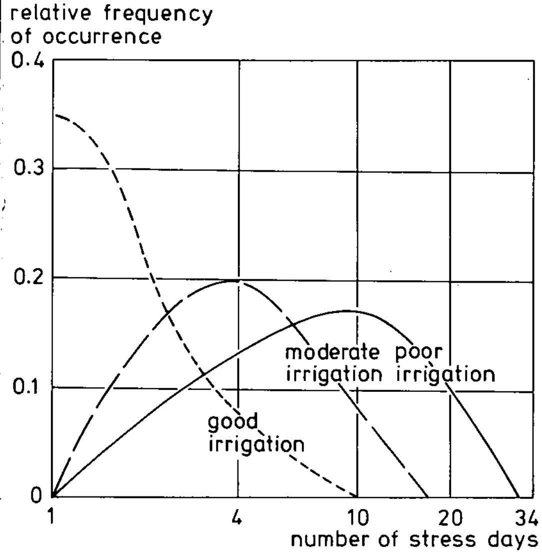


Figure 9.
Relative frequency distribution of days with serious water shortage for different standards of irrigation, dry season (ROSEGRANT 1977).

GRANT (1977) and cited by LUNING (1978) in which a production function for modern rice varieties was estimated from a combination of data from research and from small rice farms in Central Luzon. Separate functions were estimated for the wet and dry seasons and for irrigated and rainfed crops. This allows crop yields to be expressed as a function of such factors as initial yield level, nitrogen fertilization, number of days with serious moisture stress, solar radiation, insect damage, and typhoon damage. Used in establishing the production function were time series of meteorological data, data from representative irrigation systems, interviews with farmers on insect and typhoon damage, and data from research stations (on nitrogen response). Frequency distributions were established for independent variables (sunshine, insect and typhoon damage, moisture stress duration) under varying standards of water management. An illustration of the moisture stress duration variable is given in Figure 9.

Figure 10 illustrates the use of such frequency distributions in establishing the relation between crop yield and nitrogen levels.

Like all the previously cited examples, the Philippine study concerns factors that are environment-determined. None of the examples considers the farmers's attitude towards risk and uncertainty. LUNING (1978) describes such methodology as assessments of 'objective probability' as against assessments of 'subjective probability', which are based on the farmer's decision model. As yet, we know very little about how the farmer, when confronted with a number of alternatives, arrives at his final decision. Slowly we are beginning to grasp the risks he is running in his environment, but we are not able to predict how he will react.

Avenues for the future

Whilst it is obvious that much progress has been made in understanding the soil-water-plant continuum, much still remains to be done before we arrive at the future state as envisaged by SPLINTER (1976):

'We can look for computer-assisted farm management practices to include irrigation, application of fertilizer, application strategies for insecticides, herbicides, and fungicides. We can expect electronic monitoring of the water status in fields and the water status of the plant canopy to be fed to a central computer for a decision-making by the individual farmer. We can see an increased level of technology going into the machines and devices for applying irrigation water, for laying out tile fields, and for laying out and designing terraces with greater precision. As our demand for food doubles over the next 25 years, we can expect the pressures to push research and development in the soil and water area to the forefront'.

In the meantime, however, some disquieting observations have been made. GRANT (1979) notes that in parts of the U.S.A. conservation practices are being abandoned. Terracing, wind breaks, contour ploughing are no longer practised because of the use of centre pivot sprinkling equipment and agricultural machinery that requires large fields of certain dimensions.

Farmers' recent inclination towards short-term profits, brought about by market structures and price policies, is also a contributing factor.

For the immediate future, we can expect that major stress will be placed on the conservation of water resources and on low energy bills. At the same time, there will be increased pressure on soil and water research to produce knowledge that will serve an ever more sophisticated agricultural system. In the developed countries, farms

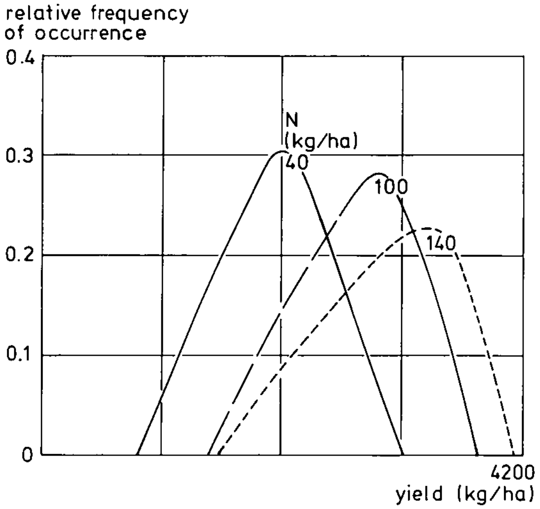


Figure 10.
Crop yield distribution for different N-levels, average standard of irrigation, dry season (ROSEGRANT 1977).

will be operated by university graduates, as agricultural production becomes increasingly industrialized and mechanized as a substitute for labour.

But what will happen in the developing countries? How will they cope with the need for a vast expansion of their food production? What can be done to help?

Efforts are underway to provide developing countries with an early warning system if possible crop failures and resulting food shortages are predicted. In exchange for the supply of meteorological and crop statistical data, these countries obtain predictions of crop yields and crop performances. Inherent to this procedure, as pointed out by many, is the danger that such information may be misused for political purposes. There is a need for some form of built-in protection for the developing countries so that the exercise will serve its original purpose only.

Because of the lack of funds and facilities and the shortage of qualified people, it cannot be expected that developing countries will conduct the intensive research that is being done in the developed countries. Nor is there any need to do so. Much of it would be mere duplication. What is needed is the development of methods that will allow research results, obtained under certain conditions of climate, soils, and crops, to be transferred to other places where basic data on such conditions are scarce.

Although this will be an important step in the right direction, the advances made in the western world can only be of value to the third world if irrigation water can be carefully controlled. As this will require heavy investments in irrigation system design and intensive training activities, it is difficult to be optimistic about the short-term contribution that western research can make to an increased food production in the developing countries. Truly appropriate technologies in this field have yet to be developed.

Although an enormous amount of research is necessary to establish the farmer's dependence on environmental factors, at least the methodologies and techniques to do so are now becoming available. But the practical application of such work to the millions of small farmers in the developing world is limited by a lack of knowledge of the farmer's decision model. Especially in irrigated agriculture, where the farmer is dependent on outside management, much more needs to be known about his attitude towards risk and uncertainty. More knowledge on this subject will lead to socially acceptable improvements in the organization of irrigation projects— improvements that must precede any technological steps towards optimum crop production.

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The use of saline water for irrigation

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Introduction

The availability of an adequate quantity of decent quality water is an indispensable renewable natural resource for plant growth. In some parts of the world the problems of water quality are more severe than the problems of water availability (BATISSE 1974). Arid and semi-arid countries, in particular, are facing the exhaustion of their natural water resources and are being forced to use poor quality water for their irrigated agriculture. The result is often disastrous as extensive productive regions become salinized and go out of production.

Water quality problems are mainly created by dissolved salts and by plant nutrients. Of the numerous examples, the following are just a few:

- In the Rajasthan region in India about 56 per cent of the total irrigated area is salt-affected through the continuous use of poor quality irrigation water (PALIWAL 1972)
- In Israel no additional water resources remain to be developed and the use of poor quality water is gradually increasing
- In the U.S.A. a 20-year study of the Rio Grande River showed a tenfold increase in the mean annual salt concentration, attributed almost entirely to irrigation return flow (WILCOX 1962)
- On the Caribbean island of Curaçao heavy overpumping of groundwater has caused a degradation of the groundwater quality and an intrusion of seawater at sites along the coast
- In various countries the increased use of fertilizers has led to harmful concentrations of nitrogen and phosphorus in irrigation return flow and has caused water quality problems in both surface and groundwaters

In fact, the improper use of water by man has contributed more to the salinization of land than has the inherited salinity by natural causes. HART (1974) states that 'environmental degradation' has generally occurred because of a lack of concern for the mechanisms by which man's actions interact with his environment'. Against this background it is understandable that in circumstances where saline water has to be used for irrigation, great care is nowadays being taken to prevent the accumulation of harmful amounts of salt in the soil.

The use of saline water for irrigation is not a new development. Farmers in parts of North Africa and the Middle East have been using it for centuries. They learned from experience how to use this water without the risk of salinizing the soil and without jeopardizing their crop yields. Those farmers did not have modern methods of measuring the salt content of water and soil. At best they tasted the water to determine how salty it was, and learned by trial and error whether they could use it successfully.

In the future, as water of good quality becomes scarcer and will probably have to be reserved for man and industry, it can be expected that saline water, or at least water of poor quality, will be increasingly used for irrigation.

The definition of saline water is, in a sense, rather arbitrary because irrigation water always contains some salts. Saline water is generally defined as water containing more than 1 to 1.5 g salts per litre, which corresponds with an electrical conductivity (EC) of 1.5 to 2.3 mmhos/cm. The total salt content, however, is not the only criterion for determining the suitability of the water for irrigation. All following factors should be considered:

- the quality of the water
- the soil
- the climate
- the crops
- the irrigation and drainage conditions
- the management practices of the farmer

No absolute criteria exist for these factors, in the sense that a given quality water, soil, or crop is never suitable for irrigation. The various factors interact, as will be discussed below.

Water quality

Total salt content

The total salt content of irrigation water indicates the total of dissolved salts whereby Ca, Mg, K, Na, Cl, SO_4, HCO_3, and occasionally NO_3 account for 99 per cent of the salt content of most waters. The total salt content of irrigation water strongly influences the salinity of the soil. In a long-term experiment on a silty clay loam in northern Tunisia (UNESCO 1970) four different qualities of water were used, their total salt contents being 0.2, 1.3, 2.3, and 3.5 g/l (Figure 1). The soil in the upper 40 cm has clearly different salt contents for the four different qualities of water, although in the deeper horizons the differences are less. Obvious seasonal fluctuations in salt content occur in the upper layer due to a more intensive leaching in the winter. The different salt contents in consecutive years are due to changes in leaching which, in their turn, are the result of

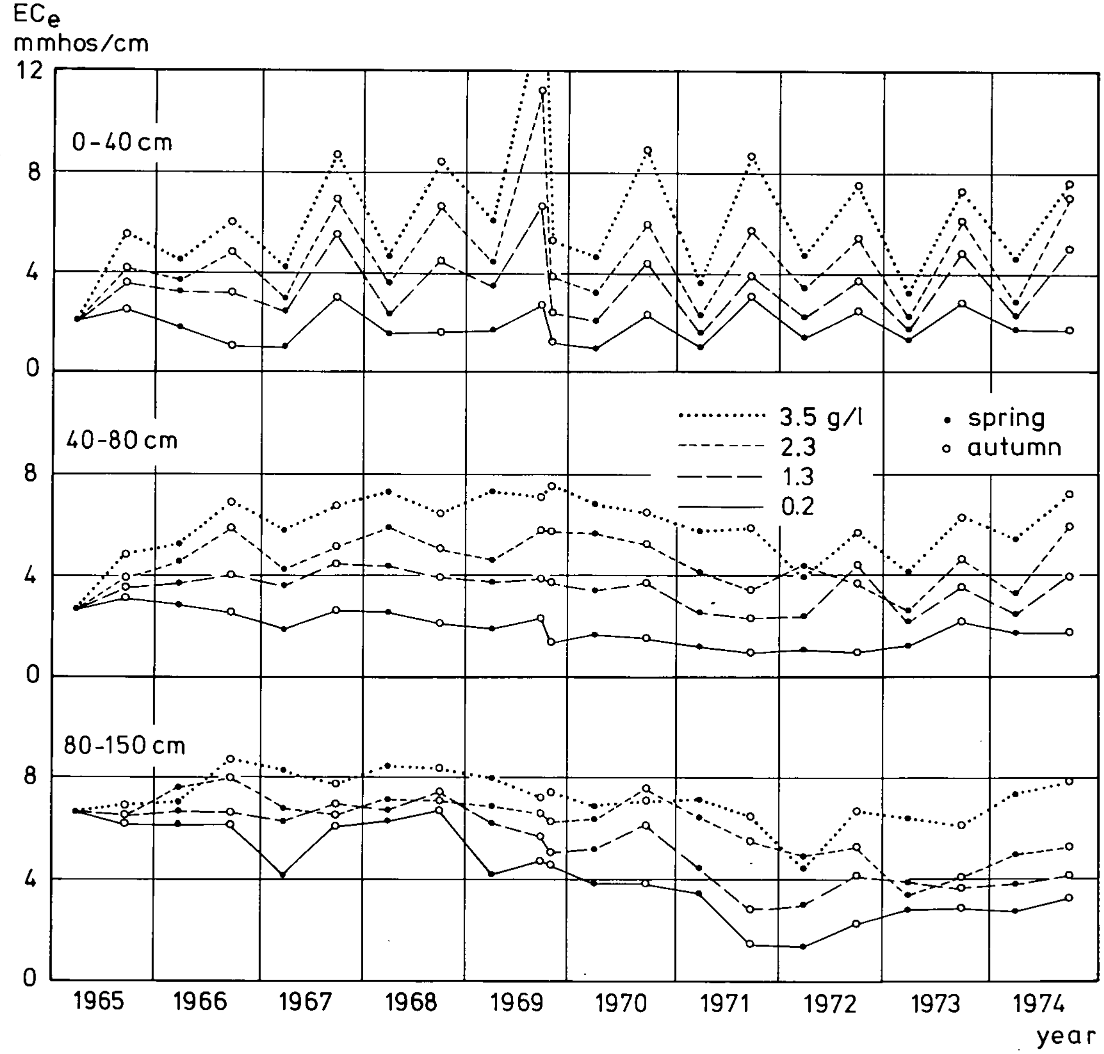
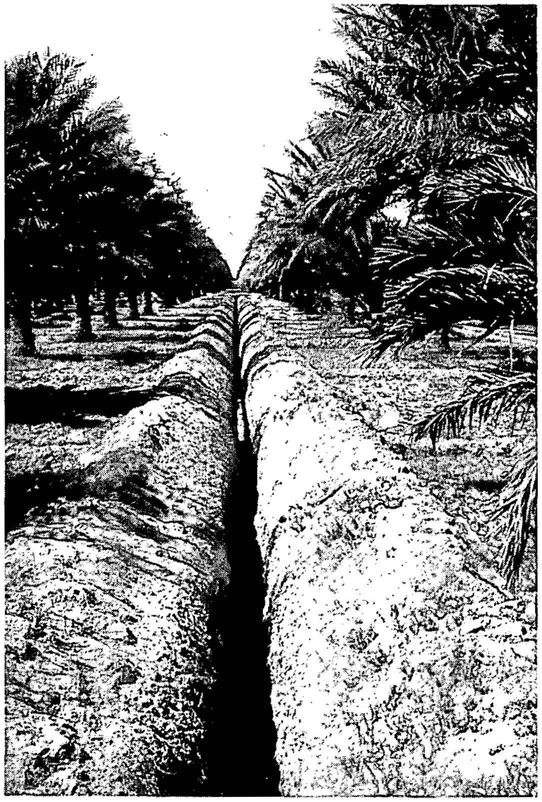


Figure 1.
Development of EC_e per layer. Water quality test in Tunisia (based on data from UNESCO 1970).

Date palm oasis in southern Tunisia, irrigated with water containing 2 g/l salts. The palms suffer from excess salts due to irrigation with saline water, insufficient water availability, and lack of drainage



The same after the irrigation water supply is improved and a drainage system is installed.

the irrigation method used and the quantity of water applied – factors related to the crops that are grown.

Another example is an experiment in the Punjab (Pakistan) which also used four water qualities with total salt contents: 0.175, 1.0, 2.0, and 2.7 g/l. Figure 2 shows the average salt content of the layers 0–30, 30–90, and 90–150 cm during the first three years of the experiment (de MOOY et al. 1975).

These examples show that the salt content of the soil increases as the salt content of the irrigation water increases. However, the salt content of the soil also depends on the leaching fraction. If, therefore, the leaching fraction varies strongly, the relation between the salt content of the irrigation water and that of the soil cannot be used for precise predictions of soil salinity (PALIWAL and GANDHI 1973).

Chemical composition

In considering the chemical composition of irrigation water, one must consider both the total quantity of the various ions and the mutual proportion in which they occur. If ions like sodium, chloride, and boron occur in large quantities, they may have direct toxic effects on the crops. Most sensitive in this respect are fruit trees and other woody perennial crops, in the leaves of which these toxic ions concentrate, causing the leaves to dessicate and die.

Apart from the direct toxic effect that sodium may exert on the crop, it also influences the soil structure and thus indirectly affects the crop. In this respect the mutual ion proportion of sodium to calcium and magnesium must be considered. This ratio can be expressed by the 'Sodium Adsorption Ratio' SAR, i.e. the ratio of the sodium concentration in milli-equivalent per litre (meq/l) and the square root of the half concentration of calcium and magnesium (RICHARDS 1954). If the SAR of the soil moisture increases, more sodium will be adsorbed by the soil complex, thereby negatively affecting the soil structure. A relation exists between the SAR of the soil moisture and the 'Exchangeable Sodium Percentage' (ESP) of the soil. The ESP, which is used as a criterion of sodicity in the soil, is defined as the amount of exchangeable sodium in the soil expressed as a percentage of the cation exchange capacity. The SAR of the soil moisture depends, in its turn, on the SAR of the irrigation water and is greater because the soil moisture has a higher salt concentration. Provided that the proportions of the ions remain constant, the SAR increases with the square root of the total salt concentration. The relation between the SAR of the irrigation water and the ESP of the soil varies with the nature of the adsorption complex of the soil and with the irrigation and drainage conditions, which together determine the concentration factor of the soil moisture. As well, rainfall and capillary rise from the

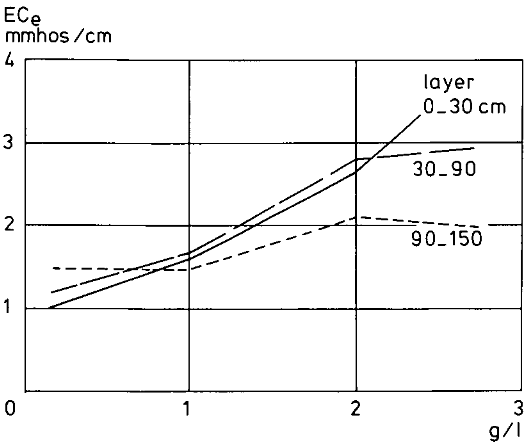


Figure 2.
Relation between soil salinity, expressed as EC_e in mmhos/cm, and salt content of irrigation water (based on data from de MOOY et al. 1975).

subsoil may play a role.

Figure 3 A illustrates the influence that the SAR of the irrigation water has on the ESP of the soil. This example is taken from the earlier mentioned experiment with four water qualities in Tunisia (UNESCO 1970). At the end of the first summer season, the ESP had already reached a rather constant level, the minor seasonal fluctuations being due to differences in leaching fraction. More leaching took place in winter, resulting in a lower concentration factor of salt in the soil moisture; rainfall also contributed to the water movement. Figure 3 B shows that the ESP increases with depth and that the differences between the ESP values become smaller owing to an increase in the concentration of the soil moisture and to the initial salt content of the soil.

The SAR of the soil moisture may differ considerably from the SAR of the irrigation water. If the irrigation water has a high concentration of carbonate and bicarbonate ions and if this water becomes concentrated as soil moisture, calcium and magnesium precipitate as carbonates when the solubility product is exceeded. Calcium and magnesium are thus withdrawn from the soil solution and the SAR value increases much more than in case of concentration without precipitation. The excess of carbonate and bicarbonate ions with respect to calcium and magnesium ions was originally characterized by EATON (1950) with the term 'Residual Sodium Carbonate' (RSC), which is the sum of carbonates and bicarbonates minus the sum of calcium and magnesium in meq/l. As the RSC increases the SAR of the soil moisture increases and makes the water less suitable for irrigation.

A shortcoming of the SAR concept is that the SAR values are supposed to indicate the sodium hazard of the water, but in fact they do not reveal whether residual sodium carbonate is present.

The SAR concept was therefore modified and a new term 'the adjusted SAR' introduced, incorporating the effect of carbonate and bicarbonate in the SAR equation (BOWER et al. 1965; AYERS and WESTCOT 1976). The introduction of the SAR_{adj} concept means an improvement on the old concept, although recent research has shown that it leads to a somewhat overestimated sodicity hazard (OSTER and RHOADES 1977).

Irrigation water in which the concentration of carbonate and bicarbonate ions exceeds that of calcium and magnesium ions, as in Venezuela (PLA 1968), often shows a low total salt content and a low SAR value. Using the total salt content as a criterion for suitability, we would classify this water as non-saline and therefore suitable for irrigation. But this would be wrong because the composition of the salt is unfavourable as indicated by the RSC and SAR_{adj}, which is higher than the SAR.

This type of water is, in fact, much more dangerous than water with a higher salt content but with a favourable chemical composition. If the chemical composition of the water is unfavourable, problems of soil structure may arise and the permeability of the soil may decrease. This reduces the possibility of leaching the soil, which, if neglected in the irrigation process, will soon cause the salt content of the soil to rise to unacceptable levels. In some regions of India and Pakistan, the water has both a high total salt content and an unfavourable chemical composition because of a high content of carbonate and bicar-

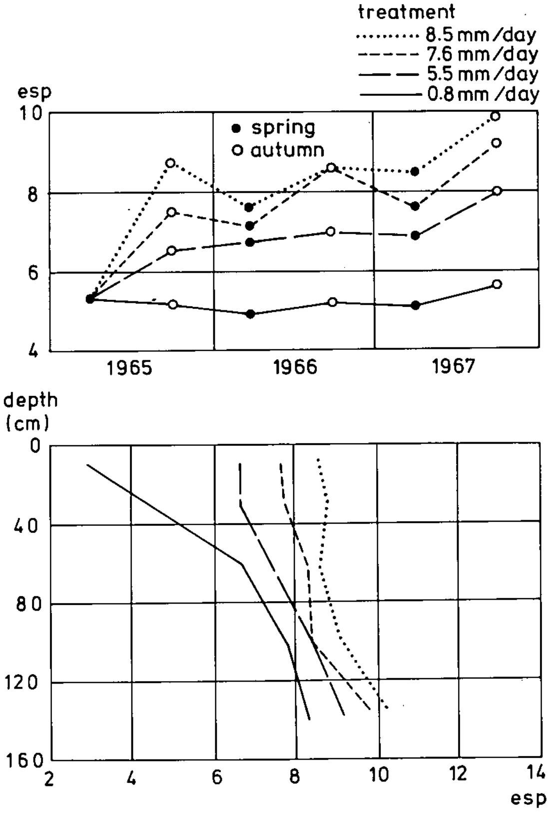


Figure 3.
Water quality test in Tunisia (UNESCO 1970).

bonate ions, or, as in Tunisia and Libya, it has a. high sodium content. Such waters can only be used successfully if salt-tolerant crops are grown on light-textured soils with a good permeability. There, because the adsorption complex is almost lacking, the soil's structure and permeability are hardly affected by the excess of sodium in the soil moisture.

An unfavourable chemical composition of the water can be remedied by applying gypsum, either in the irrigation water or on the soil. But gypsum is not always available or may be too expensive for the farmer.

The above discussion illustrates that the interaction between the chemical composition of the water, crops, soil, and means of the farmer all play a role in determining the suitability of water for irrigation.

Soils

As mentioned earlier, poor quality water can only be used on permeable soils. The key point of the percolation process is that the permeability of the soil must make it possible to wash the soil and leach the salts from the rootzone. The extra quantities of water needed for leaching can be calculated, but if the permeability of the soil is low, this extra water may stagnate on the surface, causing the crops to suffer from waterlogging without any leaching taking place.

The structure and permeability of the soil must be good and remain good under long periods of irrigation. If the SAR of the soil moisture increases through an unfavourable chemical composition of the irrigation water, it may be necessary to restrict the use of such water to soils with a low clay content. Such soils will have a small adsorption complex and their structure will therefore hardly be affected by the composition of the soil moisture. Owing to their structure, heavy and medium-heavy clay soils may originally have a fair permeability, but if their structure deteriorates, it will strongly affect their permeability.

As the total salt content of the irrigation water increases, so too does the leaching requirement, and with that the permeability requirement of the soil. The poorer the quality of the water, the higher the requirements of the soil structure to maintain a fair to good permeability. These requirements explain why the use of saline water or water of poor chemical composition is generally restricted to light soils with a good permeability.

Calcium in some form is often used to reclaim sodic soils, the most common form being gypsum. Lime, owing to its low solubility, is less often used, although by applying organic matter (manure or green manure), which increases the CO_2 content of the soil air, the solubility of the lime can be improved. On lime-bearing soils sulphur compounds can also be applied, which, after oxidation to sulphuric acid, form gypsum with the available lime.

Experiments in India have shown that soils with very high ESP values can be gradually reclaimed by applying gypsum or pyrite. Initially these soils, at least in their upper 0.50 m, belong to the saline sodic soils. After leaching, a sodic soil is left whose ESP may vary between 50 and 100. Amendments of gypsum or pyrite can gradually reduce these high values. Careful irrigation with small amounts of water (because of the low infiltration rates) have proved to give good yields of crops tolerant to a high ESP, for example rice (CSSRI 1977).

Climate

Evaporation, rainfall, and temperature are the most important climatological components to be considered in determining the suitability of water for irrigation. A high evaporation rate means that more water and thus more salt will be applied than when evaporation is low. In general, this will cause a higher salt content in the soil, notwithstanding leaching.

If water with a high salt content is used, it may be wise to grow winter crops or crops that do not need irrigation during periods of maximum evaporation. For instance, in Tunisia it was possible to cease irrigation of alfalfa from early July to the end of August and to harvest seed instead of hay in that period.

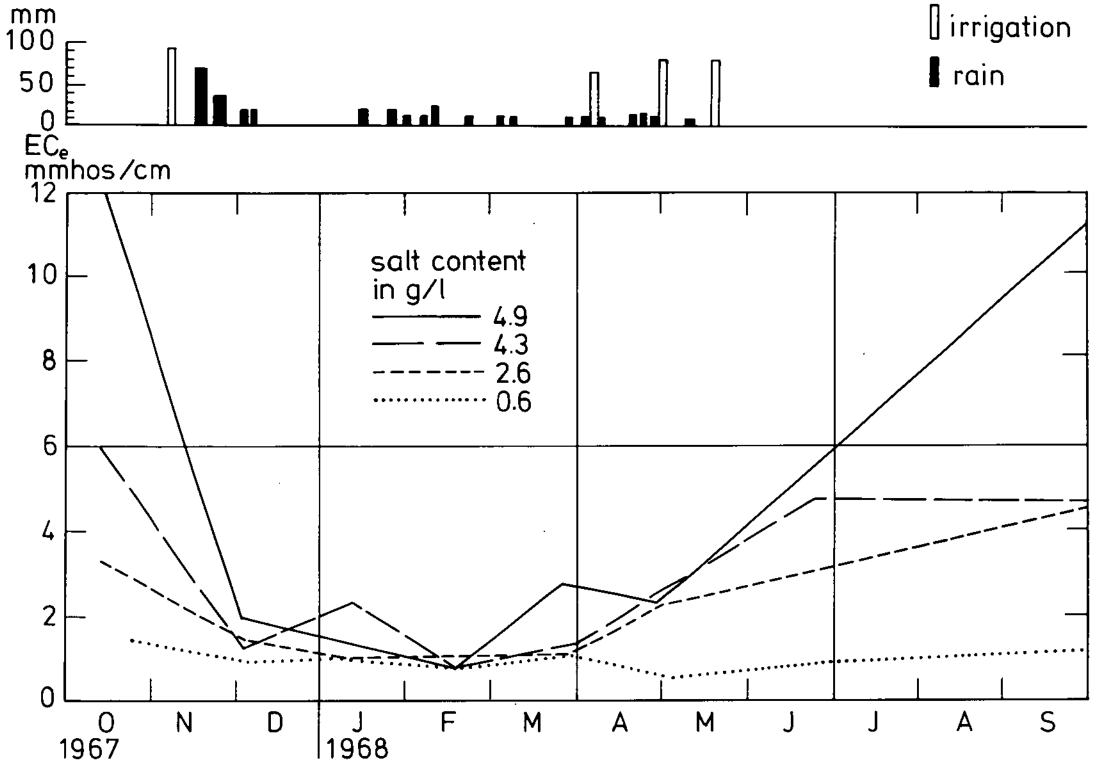


Figure 4.
Fluctuation of soil salinity (EC_e: 0–25 cm layer) under influence of rainfall and irrigation on land cultivated with wheat in southern Iran (van AART and OOSTERKAMP 1968).

Rain may contribute substantially to the leaching process, provided it falls during periods of low evaporation as happens in regions around the Mediterranean Sea and in the Middle East. If the soil is irrigated at the beginning of the rainy season, the soil moisture content will then be approximately at field capacity and most of the rainwater will contribute to the leaching instead of being needed to make up the soil moisture deficit. This is illustrated by Figure 4 which shows the decrease of soil salinity under the influence of winter rainfall (347 mm) in southern Iran (van AART and OOSTERKAMP 1968).

Crops grown during relatively cool periods of the year show, in general, a greater salt tolerance than when grown in warm periods. Summer tomatoes have proved to be more sensitive to blossom-end-rot than spring or fall tomatoes (UNESCO 1970). This disease is caused by a lack of calcium, which occurs when saline water is used at high temperatures (BERNSTEIN 1964).

Crops

The osmotic potential of the soil moisture increases as the salt content of the soil moisture increases. If this happens, less water will be available to the plant, thus reducing its growth and causing a yield depression. Usually the vegetative growth is more seriously hampered than the formation of seed. Apart from the osmotic effect, the salt can exert a toxic effect on crop growth.

In principle, the relation between yield depression and salt content is an S-shaped curve. In the yield depression range of 5 to 75 per cent, this relation is approximately linear, as is shown in Figure 5 (MAAS and HOFFMAN 1977).

At yield depressions as high as 50 per cent, the crops may still develop regularly and homogeneously without visible salt damage. Consequently, one is apt to underestimate the damage caused by the salt, which appears only at harvest and after the yield is compared with that obtained under non-saline conditions. The reduced crop growth may thus be erroneously ascribed to other factors. The experiment with four different water qualities in Tunisia showed that the maize irrigated with the 3.5 g/l water was less developed and ripened earlier than the maize irrigated with the 0.3 g/l water. The yield depression was about 50 per cent. Similar results were obtained with wheat in experiments in southern Iran, where water with salt contents of 0.6 and 4.2 g/l was used (FAO 1972). Notwithstanding the yield depressions the crops in the above examples were regularly developed and did not show the stunted growth or discoloration usually observed on saline soils. If growth is stunted,

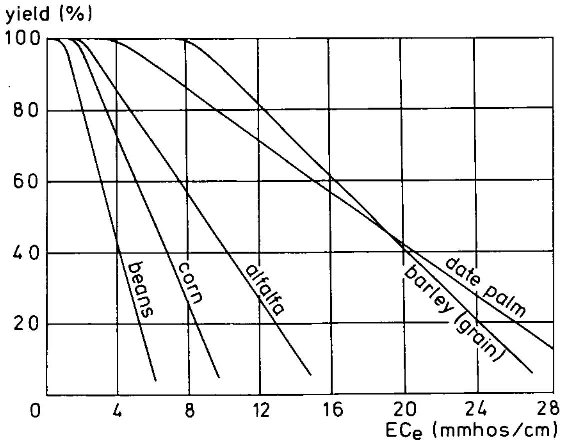


Figure 5.
Relation between yield and salinity (adapted from MAAS and HOFFMAN 1977).

the yield depression is much greater than 50 per cent.

From research conducted in different countries under different soil and climatic conditions, it has been found that the classification of crops into low, medium, and high salt-tolerance classes agrees well. Differences in the various classifications can often be ascribed to differences in variety. For instance, alfalfa in the U.S.A. is classified as medium salt-tolerant, whereas in North African and Middle Eastern countries it is reckoned among the highly salt-tolerant crops. Local varieties of wheat and barley in those countries usually also have a high salt tolerance.

Most vegetable crops have a low salt tolerance, which can be explained by the osmotic effect. Vegetable yields are usually highest at relatively low moisture potentials. With an increasing salt content of the soil solution, the osmotic effect causes a rapid rise in moisture potential.

In the last decades little research has been done on the development of salt-resistant crop varieties, the main research efforts being devoted toward making the environment fit for the growth of conventional salt-sensitive crops. Only in very recent years has a new approach been made to modify the crops genetically to make them fit for saline environments (EPSTEIN 1978).

Irrigation and drainage conditions

Leaching

As already mentioned, the salt content of the soil depends not only on the salt content of the irrigation water but also on the leaching fraction. Figure 6 shows the results of an irrigation experiment with four different quantities of water corresponding with a daily water application of 4, 6, 8, and 10 mm, all with a salt content of 2.3 g/l (UNESCO 1970).

The evaporation was approximately 7 mm/day. Clear differences were observed in the salt content of the soil, and also clear increases of the salt content with depth.

The increase in salt content with depth, which can be expected under long-term irrigation, occurs because the uptake of moisture by the plants decreases with depth. Hence the quantity of water percolating through the rootzone decreases with depth. If we assume that 100 per cent of the irrigation water infiltrates into the top layer, only about 25 per cent may percolate through the bottom of the rootzone to the subsoil.

To calculate the required quantity of leaching water, the simplest method is to regard the rootzone as a single layer in which one wants to maintain a salt concentration that is acceptable to the plants. This leads to the well-known salt balance equation (RICHARDS 1954) in which the quantity of salt supplied by the irrigation water is considered equal to the quantity of salt discharged by the percolation water. In reality, the salt content of the upper soil layers, which take up most of the water, is lower than the average salt content while that of the deeper layers is higher. The one-layer concept of the rootzone thus leads to an overestimate of the required quantity of leaching water.

Part of the leaching water, however, quickly percolates through the cracks and rootholes, hardly removing any salt. As this part of the leaching water is not effective in the leaching process (BOUMANS 1963; UNESCO 1970) it therefore compensates for the overestimate of the quantity of leaching water made by regarding the rootzone as a single layer. Only if nearly all the water contributed to the leaching process – and this would depend on the soil structure and the irrigation method applied – would it be justified to reduce the quantity of leaching water.

Theoretically, so much leaching water could be applied and the salt content of the soil so reduced that the soil moisture finally attains the same concentration as the irrigation water. In practice, however, this is impossible because it would cause waterlogging on most soils. One should therefore accept the salt content of the soil that corresponds with that of the irrigation water and with the quantity of leaching water that the crop can tolerate, adapting the choice of crops accordingly.

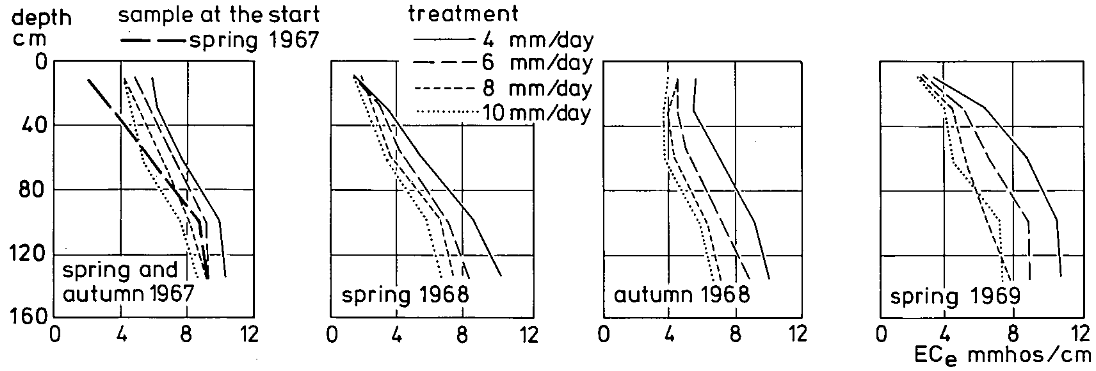


Figure 6.
Irrigation test in Tunisia (UNESCO 1970).

If the rootzone is regarded not as one layer but as several layers, it can be calculated that, under good irrigation and drainage management, the effective leaching water should be about 15 per cent of the irrigation water. Taking into account that only part of the leaching water is effective, the total quantity of leaching water should be about 25 per cent of the irrigation water. It is then possible to maintain the soil solution at three to four times that of the irrigation water, which will suffice provided there is good irrigation and drainage management.

Leaching can be done in one of two ways: by applying extra water either frequently, (e.g. at each irrigation) or seasonally. With frequent leaching, more water must be applied than the plant needs for evapotranspiration. This raises the peak use of water during summer when water is usually scanty, and also increases the salt supply. With seasonal leaching, the operation can be conducted in periods of low evaporation when water may be more plentiful and when rain may contribute to the leaching process.

Experiments conducted in Tunisia under different soil and climatic conditions showed that seasonal leaching gave excellent results (UNESCO 1970). The salt content of the soil was only slightly higher and the crop yield was not, or only slightly, lower than with frequent leaching. These findings agreed with local practice, which uses salt water economically in summer and makes use of the winter rains.

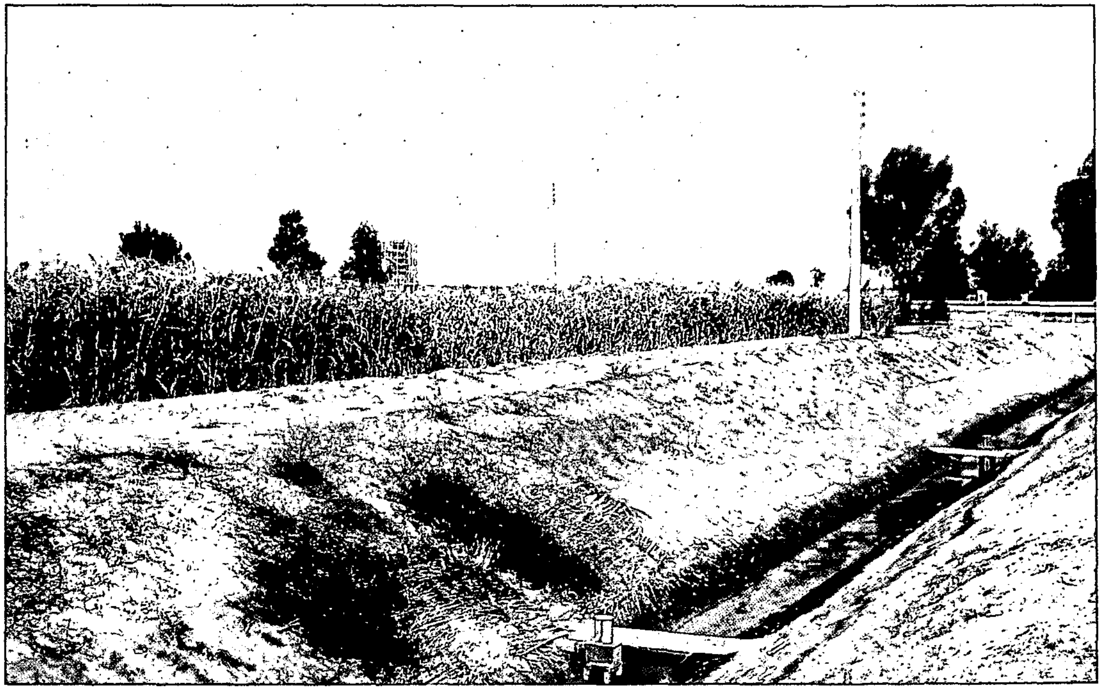
Irrigation methods

With frequent irrigations the soil moisture content will be higher and the salt concentration of the soil solution lower than with less frequent irrigations. The osmotic potential will thus remain lower, thereby favouring crop growth. This procedure produces a more marked effect on light textured soils than on medium and heavy textured soils, where smaller fluctuations in moisture content occur.

Surface irrigation is the oldest and most widespread irrigation method and can also be used for saline water. Its disadvantage is that because the soil surface serves as a transport medium, water quantities cannot be precisely controlled because of differences in the soil's infiltration rate. The quantity of water applied must be large enough to cover the whole field, but if applied frequently, the crops may suffer from excess water, especially on medium and heavy textured soils, while particularly on light textured soils the water use will be excessive.

Sprinkling offers better possibilities for frequent irrigation because it is easier to control the water quantities, thus preventing too much water from being applied. At high temperatures, however, sprinkling with saline water may cause the leaves of the crops to burn. Experiments in Tunisia showed that no leaf burning occurred when water of 4 g/l was sprinkled at temperatures less than 20 to 22 °C. This means that sprinkling with saline water can be applied on winter crops, and on summer crops in their first growth stage.

Another advantage of sprinkling is that, owing to the small quantities of water applied, the struc-



Maize experiment in northern Tunisia (Cherfech); qualities of irrigation water: 0.2 and 3.5 g/l salt.

Damage to coconut plantation due to the high salinity of irrigation water along the coast of Saurashtra, State of Gujarat, India.

ture of poor or sensitive soils deteriorates less than with surface irrigation, and that the germination and emergence of crops are usually better. Once a good crop stand has been reached, surface irrigation can again be applied, thus making it unnecessary to install a permanent sprinkling system, instead of which mobile units can be used, as is done in the Imperial Valley of California (MARSH et al. 1975) and in Tunisia (UNESCO 1970).

Drip irrigation makes possible a regular and very frequent water supply, which can lead to a nearly stable salt content of the soil solution at the lowest possible level because the moisture content of the soil approximately corresponds with field capacity. Since the wetted soil volume is leached continuously, the salts move and accumulate at the rim of the wetted soil body. Drip irrigation is particularly advantageous on light-textured soils with a low water-holding capacity. Even better than with sprinkling, drip irrigation can provide a regular moisture supply, without causing leaf burning. This has been confirmed by several reports (BERNSTEIN and FRANCOIS 1973; 1975; GOLDBERG and SHMUELI 1970). As drip irrigation supplies water to the site of the plant and not over the whole field, weed growth is restricted. If rainfall is insufficient to leach the salt from the rim of the wetted soil body, other ways of leaching must be found, with due consideration given to their feasibility, costs, and effectiveness (FAO 1973).

Drainage

Drainage serves to dispose of the leaching water that percolates through the root zone. Drainage can be either natural, as when river levees are drained by the adjacent river, or artificial, either through canals, ditches, and pipes (horizontal drainage) or through a system of tubewells fitted with pumps (vertical drainage). Drainage is the necessary complement to irrigation. This is true for all types of irrigation, not only for irrigation with saline water. But, if drainage is poor and the irrigation water saline, soil salinity problems will be sooner created than when the irrigation water is fresh. If saline water is to be used in a new irrigation project, the installation of a drainage system is even more urgent than otherwise. Postponing drainage in such a project can lead to disaster.

Management practices

Good management practices aim at obtaining a good stand of the crop by a rapid and homogeneous germination of the seed and emergence of the seedlings. A failure at this stage generally leads to a poor stand and a considerable yield decrease. This applies to all crops – non-irrigated as well as irrigated – but especially to crops irrigated with saline water. Mistakes made when irrigating with saline water have a far more harmful effect than those made with fresh water. Salinity, although it will usually delay germination, does not prevent it. The emergence of the seedlings, however, can suffer far more severely from unfavourable soil and weather conditions than from salinity; such conditions can even prevent emergence. In spring, for example, a relatively low temperature may occur in combination with a strong drying wind which forms a crust at the soil surface. The young seedlings, whose germination was delayed by the salinity and the low temperature, may be caught in the crust that has formed in the meantime. The non-uniformity of the plant emergence then makes it necessary to irrigate more frequently and this increases the hazard of the plants suffocating.

A good emergence of the seedlings with the shortest delay is of primary importance for the development of the crop. Measures that can help to achieve it are the following:

- Improving the soil structure through good cultural practices; crust formation caused by applying large quantities of water during the first irrigation after sowing can be prevented by sprinkling with small amounts at a low rate
- Good land grading, which allows a homogeneous moisture distribution to be obtained and prevents water from stagnating at the surface
- Sowing at favourable temperatures so as to shorten the time between sowing and seedling emergence

If the irrigation water has a composition that negatively affects the soil structure, the application of gypsum or organic manure may improve matters.

Since the infiltration rate strongly depends on the structure of the top layer, tillage should aim at keeping this layer open. To prevent its structure from deteriorating, irrigation methods that allow small quantities of water to be applied should be chosen.

It is obvious that management practices depend on the skills of the farmers and on the implements they have at their disposal. When deciding whether saline water can be used under local conditions, these two factors must also be considered.

Epilogue

In the last decades a better insight has been gained into the factors that affect the use of saline water for irrigation. This is clear when one compares the well-known classification of irrigation water by RICHARDS (1954) with the classification standards given by AYERS and WESTCOT (1976). In Richards's handbook one can find almost all the factors that play a role in determining the suitability of water for irrigation, but one gets the impression that the users of this handbook only take the salt and sodium content of the water into account. Since the use of saline water causes problems, they classify this water as unsuitable, and judge the possibility of using it on the basis of a laboratory analysis, without taking into consideration other local factors like the soil, the adaptation of the cropping pattern, etc.

AYERS and WESTCOT emphasize the problems one faces when using saline water, indicating that they become more severe as the salt content of the water increases or its composition becomes less favourable, but they also discuss the possibilities of solving these problems. This new approach provides guidelines that consider each problem and its solution separately. The guidelines are a tool developed to help the trained field man and scientist to better understand, characterize, interpret, and improve soil and plant response under a given set of conditions.They stress that the decision whether to use saline water depends on the conditions at farm level, i.e. the decision must be made in terms of the specific use and the potential hazard to crop production under local conditions. The use of saline water may constitute a considerable restraint, but the increase in soil salinity and in the exchangeable sodium at the adsorption complex are not irreversible processes.

Summarizing, the main conditions for the successful use of saline water are:

- soils of sufficient permeability
- crops chosen for their salt-tolerance
- good irrigation management to ensure sufficient and properly distributed water
- good drainage, either natural or artificial
- skilled and well-equipped farmers

When fresh water is used, frequently occurring defects like inadequate drainage, imperfect land levelling, and poor tillage will be disclosed only very gradually. When saline water is used, those defects will show up very rapidly as the margin of safety is much smaller.

Of course, the problems of using saline water for irrigation could be overcome by desalinizing the water. Various technical processes are nowadays available to do so. But the costs are prohibitive and are likely to remain so for some time to come. Desalinization of water for irrigation will therefore be applicable only under special circumstances and for special cash crops like vegetables. It is unlikely that desalinization will cause a break-through for the large-scale application of saline water.

Progress can perhaps be expected from the technology of breeding for salt tolerance. The development of crop varieties that are better adapted to the saline environment could cause a break-through in crop production. This new approach is at present receiving attention. Great research efforts, comparable with those for the breeding of new grain, rice, and maize varieties during the sixties, may well be justified.

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The study of effects of drainage on agriculture

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Introduction

Of the world's arable land, roughly 155 million ha have been drained (NOSENKO and ZONN 1976). FAO (1977) estimates that in irrigated regions alone 52 million ha need to be drained in the near future. With such large investments at stake it is necessary to continuously review our knowledge of drainage and of the effects it may have on soil, plant, agricultural practices, and hydrology. In this way, we can locate the possible gaps in our knowledge and try to bridge them. Recent attempts to understand the drainage-situation in the world and to determine the research needs were made by Dieleman, van Schilfgaarde, and Zaslavsky (WESSELING ed. 1979). A similar attempt will be made in this article. It is not my intention to review exhaustively all research efforts of the past, but rather to indicate the lines along which research has developed and to illustrate this with some examples.

Research on the effects of drainage can be done in two ways:

- by conducting experiments under controlled conditions, e.g. in the laboratory, in lysimeters, on experimental fields or with analog and simulation models
- by making observations in the fields, on the farms, i.e. under a wide variety of conditions.

The first kind of research identifies which factors are relevant in drainage design and evaluation. With this identification one is better able to perform the second kind of research. But, because of the wide variety of field conditions and the many interactions between them, it is possible that field observations, farm surveys, and the like lead to conclusions that differ from those found under controlled conditions. Hence, for the study of practical drainage problems, one should not rely only on the results of studies made in a uniform environment, but should check these results in a pluriform environment. In this way one can, additionally, detect relationships that cannot be discovered 'in the laboratory', or identify bottlenecks that might not have been found by a straightforward application of theory.

Research on the effects of drainage serves a dual purpose: it can show whether the installation of a drainage system is yielding the desired results, and it can lead to the development of appropriate drainage criteria so that good new drainage designs can be made.

There are many different types of drainage; for example:

- internal or field drainage versus external drainage (which mainly refers to disposal drains and outlets)
- surface drainage (which is done by land shaping) versus subsurface drainage (which is done by subsoiling or moling, or by installing pipe drains, ditches, or tubewells)
- gravity versus lift or pump drainage (which

entails important operational differences)
- interception versus relief drainage or dewatering (which entails important differences in discharge capacity)
- temporary drainage (i.e. the drainage system operates only on certain occasions) versus permanent drainage.

Any drainage system can be characterized by the alternatives in these five categories, thereby offering a large number of possible combinations. Some drainage systems have double functions. Surface drainage is most common in areas with high rainfall intensities or where soils have a low infiltration capacity, but is also applied in irrigated lands. Subsurface drainage is common both in the temperate zone and in irrigated lands. Temporary drainage systems are found in paddy fields, where rice is grown in basins of ponded water. Here drainage is normally undesirable, but on certain occasions (e.g. after exceptionally high rainfall or before harvest operations) the drainage system is put to work. To describe such a system by the five categories mentioned above, we would call it a temporary surface relief drainage system, whose internal (and possibly also external) component is based on gravity flow.

The different types of drainage systems all require their own set of design criteria and a separate research approach as to their effects. But it often happens that the same kind of system is used in different situations (we can think of drainage of tropical lands or lands in the temperate zones, drainage of arable land, grassland, clay soils, peat soils, polderland) so we may expect similarities and differences at the same time.

In irrigated lands in arid zones, for example, a subsurface drainage system helps to control salinity, whereas in humid regions salinity constitutes no problem. Also, the drainage water in irrigated lands may have a high salt concentration, which can prove detrimental to the environment. Otherwise, drainage is not much different in the two situations, serving as it does in both to maintain a well-aerated soil. In both situations, the drain discharge depends on the recharge and it is immaterial whether this recharge is produced by rainfall or irrigation, though the latter can be better controlled. Soil salinity control in irrigated land is rather a matter of correct irrigation, with drainage as a complementary factor. The expression 'drainage for salinity control' is misleading.

Methods of analysis

A simple and direct method of analysing the effects of a drainage system is to consider the influence that the drainage system's engineering variables have on crop productivity. In the following diagram, this influence is expressed as Relation A.

$$\begin{tikzcd}\text{drainage system's engineering variables} \arrow[r, "A"] & \text{crop productivity}\end{tikzcd}$$

The engineering variables depend on the kind of drainage system. For example, in a subsurface field drainage system by pipes, the variables can be depth, spacing, and diameter of the pipes.

The effects of different engineering variables can be studied step by step, e.g. by using a range of drain spacings (see Figure 3), or by simply considering the 'with' and 'without' case, i.e. by comparing crop productivity in drained and undrained land. SCHWAB et al. (1966), for instance, reported that maize production in drained land was 4000 kg/ha whereas in undrained land it was 2500 kg/ha.

Relation A, when established for a certain region, has no validity for application elsewhere because it depends on the type of soil, the climate, the crop, the hydrological conditions, and the topography of that region. However, a more universal applicability of empirical results can be promoted by introducing into Relation A more variables than just engineering and productivity. For example:

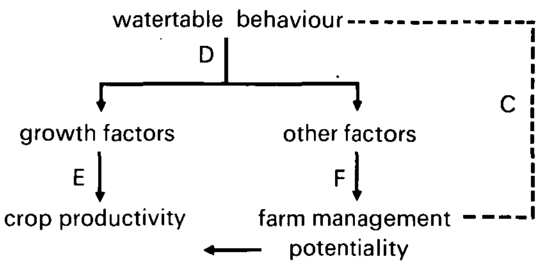
$$\begin{tikzcd}\text{drainage system's engineering variables} \arrow[r, "B"] \arrow[rr, dashed, bend left, no head, "A"] & \text{water table behaviour} \arrow[r, "C"] & \text{crop productivity.}\end{tikzcd}$$

Here, Relation A has been broken up into two other relations (B and C). The intermediate variable watertable behaviour was first introduced in about 1940, for two reasons:

- the change in watertable behaviour (or in more general terms the change in the amount of water present on or in the soil) can be considered a direct effect of a drainage system; in other words it is the first thing that happens before any other effect (like a change in crop growth or soil conditions) takes place.
- Relation B (often expressed in a form known as a drainage formula) is entirely a hydraulic relation and lends itself to the development of theroretical models; in other words one conceives certain idealized conditions and then predicts the watertable response to variations in engineering variables.

Drainage formulas have more than local value because they include variables representing natural conditions like recharge and hydraulic conductivity. With a correct assessment of the values of these variables in a certain area, the formulas can be applied under widely different conditions. These values, however, are not always easy to assess because of their generally wide variability. Besides, the more variables included in the formula, the costlier their determination becomes. The literature on surface and groundwater hydraulics and on Relation B is extensive. In fact, our knowledge of drainage formules is so vast that at the International Drainage Workshop (WESSELING ed. 1979) it was concluded that the high priority that had earlier been given to research on this subject is no longer required.

Theoretical models for Relation C (watertable-crop productivity) are practically non-existent. The relation is so complex that we must still rely on local, empirical data. Hence, Relation C, if developed in a particular region, is transferable to other regions only if the agricultural conditions are comparable. To enhance more general validity, Relation C can be broken up as follows:



The 'other factors' may, for example, be soil stability factors (workability, bearing capacity, subsidence), irrigation and leaching potentiality (important for salinity control), and hydrologic changes (seepage, runoff). In fact, growth and other factors are not entirely separable because many soil properties influence both crop productivity and farm management potentiality. Moreover, farm management influences crop productivity through the growth factors again. Hence, the above diagram simplifies the state of affairs.

Changes in growth (and other) factors are secondary effects of a drainage system. Their number is large. Restricting ourselves to the growth factors, we can summarize the secondary effects as in Figure 1.

Relations A, C, D, E, and F will be discussed further in the following sections. Relation B will not be treated as it is outside the scope of this article. Nor will the influence of drainage on the whole farming system be discussed, although, as can be seen in Figure 2, this influence can be significant. Research on the subject, however, is scarce (FOUND et al. 1976).

Direct production functions

Literature on crop production as a function of engineering variables (Relation A) is not very extensive. Investigators seem to prefer an analysis

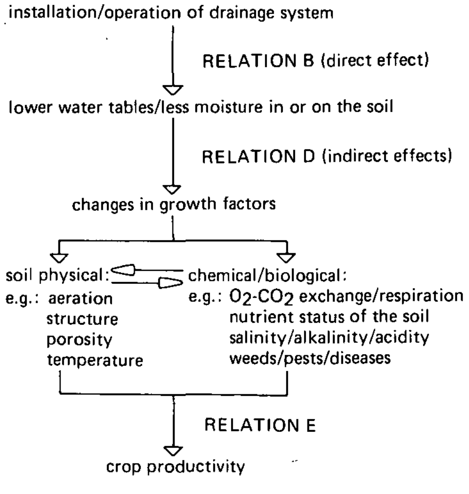


Figure 1.
Effects of a drainage system on plant growth.

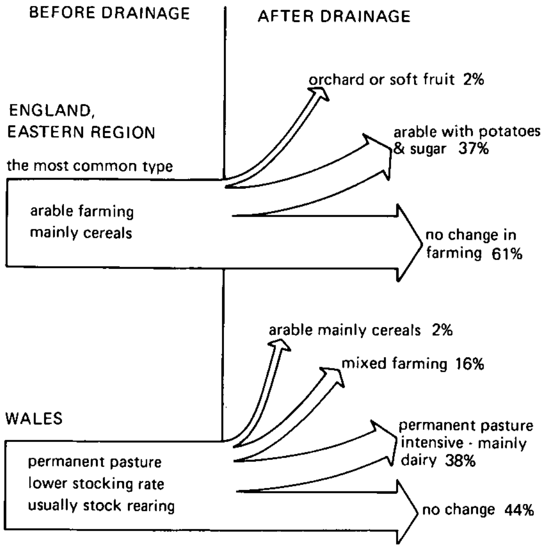


Figure 2.
Changes in farming system (FDEU 1972).

of 'with – without' cases or a study on the relation between watertable and crop production (Relation C).

An outstanding study of crop response to variations in one engineering variable (viz. drain spacing) is that reported by ERIKSSON (1979), concerning data obtained from 125 drain test fields over a period of 30 years. This kind of extensive research is not very common in the world of drainage. An example of this work is reproduced in Figure 3.

Figure 3 shows that in the range of drain spacings of 16–30 m the net benefit is practically constant. One thus has a wide range of design options. In the Swedish situation it is apparently not necessary to determine the drain spacing with any great accuracy.

TRAFFORD (1972) reviewed a number of situations in which different drainage intensities produced no significant differences in yield although the yields were clearly better than on the undrained control. DISETER and van SCHILFGAARDE (1958) found that yields of maize did not essentially differ when drain depths were 2, 3, or 4 ft with a spacing of 160 ft. These studies also indicate that no great precision in the determination of the engineering variables is required. DIELEMAN (1979) stressed that the cause of failure in drainage design is more often a lack of understanding of the broad interrelations between drainage and other farm or water management matters than the lack of precise data. The examples given above are a good illustration of his viewpoint. Drainage, evidently, is more than the determination of the correct dimensions of the system. Optimum depths and spacings of drains are probably strongly dependent on local conditions; general guides are difficult to conceive.

Another illustration of broad interrelations being more important than accurate design is given by FOUND et al. (1976). These authors analysed the benefit/cost ratio of a large number of external drains (outfalls) in Ontario, and found the ratios to vary from 0 to over 20. Except for some drains that appeared much too elaborate (over-engineering), the ratios were largely determined by the productivity of the environment and the local initiative to make use of the drainage potential.

Watertable and plant productivity

In a review article, WILLIAMSON and KRIZ (1970) reported that most of the early work in detecting relations between crop yields and the depth to the watertable (Relation C) was done in field experiments where the elements of nature could not be controlled. Thus, according to the authors, conflicting results were obtained. Since about 1940, the experiments have been conducted mainly in growth chambers, lysimeters, and controlled experimental fields. Very little work has been done on the response of crops to fluctuating watertables (WESSELING 1974). SIEBEN (1964) was one of the first to express fluctuating watertable behaviour with a single index and to relate this index to crop production (Figure 4). The value of the index SEW_{30} is found by taking the Sum of the daily Exceedances (in cm) of the Winter watertable above a level of 30 cm below the soil surface. Figure 4 shows that for SEW_{30} values of up to 500 little yield reduction occurs. For values above 500, yield depressions depend very much on the kind of crop and the year of observation.

Sieben limited the SEW values to the winter season, because his work was done in The Netherlands, where winter is the drainage season. In summertime the relation between watertable and yield would not produce information on how to drain but possibly on how to subirrigate, because in the Dutch summer evaporation exceeds rainfall.

It would seem likely that in fields with naturally fluctuating watertables the frequency of excep-

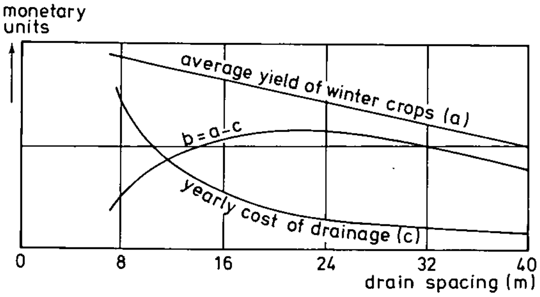


Figure 3.
Net benefit of winter crops as a function of drain spacing in a 60% clay soil in Sweden (adapted from ERIKSSON 1979).

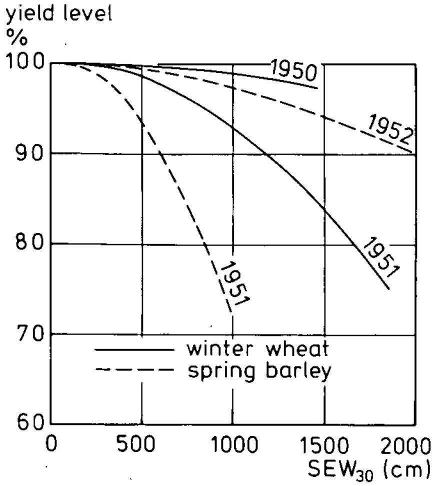


Figure 4.
Yields in relation to SEW values in The Netherlands (adapted from SIEBEN 1964).

tionally high watertables is strongly related to the average depth of the watertable: the lower the average level, the less frequently will high levels occur (FEDDES and van WIJK 1977). It may therefore be worthwhile to study plant production in relation to average watertable depths.

As is obvious from Figure 4, yields plotted against SEW values over a period of many years would produce a large scatter of points. It is unlikely that plotting the yields against average watertables would reduce the scatter (Figure 5). Nevertheless, the use of averages offers advantages over the use of extreme values in that the collection of the data and the application of drainage formulas is easier with averages.

It is regrettable that production functions are so often represented by smooth lines in a graph, with no reference to possible deviations from these lines, which might otherwise provide an extra insight into the problem. Relations showing a large scatter of data are seldom published, though there are probably more data of the kind depicted in Figure 5 than have ever been reported in our journals. True, it is hard to predict a yield from Figure 5, but this is not unrealistic because the watertable is, of course, not the only production variable involved. Moreover, the figure has interesting features.

It shows that the maximum yields (i.e. yields obtained under optimum cultivation conditions other than watertable) are less sensitive to shallow watertables than minimum yields (i.e yields obtained under adverse cultivation conditions other than watertable). All yields however, are depressed at watertables shallower than 30 cm. In the range of 30–60 cm, maximum yields are not influenced by depth, but minimum yields react sharply. This means that in this range good cultivation conditions can compensate for unfavourable groundwater conditions or good groundwater conditions can compensate for poor cultivation conditions. Beyond a depth of 60 cm yields are no longer influenced by changes in depth. In other words, in areas similar to the experimental area, drainage systems that maintain average watertables at 60 cm will be satisfactory.

In the past decades, the effects of the watertable on crop productivity have been studied mainly in small-scale experiments, which have not provided clear-cut indications for large-scale application. The experiments have, however, led to the recognition of important growth factors, as will be demonstrated in the next section.

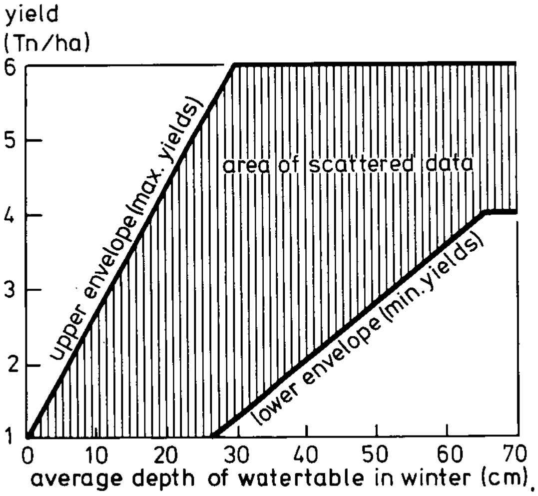


Figure 5.
The yield of grains (mainly winter wheat) on a heavy soil in England as a function of watertable depth (based on unpublished data from Drayton experiment, FDEU).

Watertable and growth factors

The study of the physical growth factors in Relation D (figure 1) has been reviewed by WESSELING (1974), van de GOOR (1972) and FEDDES (1971). It appears that the bulk of research on this subject took place concurrently with the development of drainage formulas, i.e. after about 1940, and that it emphasizes the interactions between air content of the soil, gas exchange, and temperature. Gas exchange determines the amount of oxygen in the soil, and this triggers off an enormous amount of chemical and biological reactions, in the form of oxidation and reduction of chemical compounds, plant root respiration, changes in the quality of the organic matter, etc. Soil temperature has been found to exert a great influence on seedling emergence and early frost damage.

The influence of watertable on soil structure is likewise determined by a large number of intermediate factors, while soil structure in its turn influences the aeration and aeration-dependent soil properties. WESSELING ed. (1979) presents a number of articles on the relation between drainage and soil structure. All these articles refer to

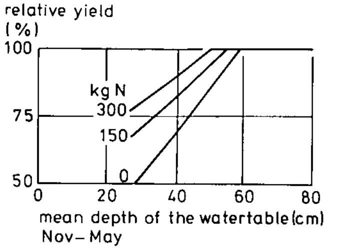


Figure 6.
Yield of 1st and 2nd cut of grass on peat soil in The Netherlands (FEDDES and van WIJK 1977).

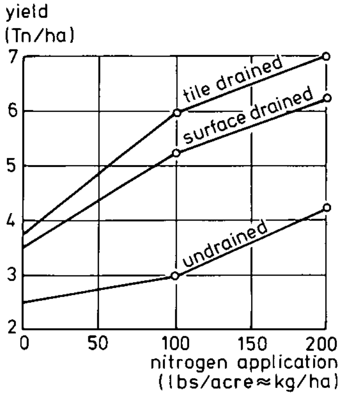


Figure 7.
Effect of drainage and N on corn yield – 3 year average (SCHWAB et al. 1966).

heavy clay soils, where the structure problem is most pronounced. The general conclusion is that drainage can produce considerable structure improvements, which in turn enhance the functioning of the drainage system.

So far it has not been possible to formulate an integral picture of all the indirect effects that drainage has on the physical or chemical properties of the soil. However, it has become clear that the indirect effects should not be investigated for isolated growth factors, but rather as a coherent complex of factors with numerous interactions. Figure 6, which refers to grassland on peat soil, an illustration of an indirect chemical effect of drainage. As seen here, nitrogen dressing can compensate for poor drainage. One can also say that the soil itself releases more nitrogen for the plant as the watertable is lower (down to a depth of about 60 cm), because with increasing depth the need for nitrogen application reduces. Van HOORN (1958) obtained a similar result for cereals on a clay soil; here the maximum nitrogen release by the soil was reached at a watertable depth of 150 cm.

SCHWAB et al. (1966) found a different result. The same amount of fertilizer produced greater yield increases in drained plots than in undrained plots (Figure 7). It seems that the relation between drainage and nitrogen status of the soil depends much on local conditions.

These examples show that drainage can make nitrogen application either unnecessary or more efficient. Indeed, drainage can influence agriculture in many respects, both through natural growth factors and through farm management potentialities. An example is the salinity control in arid lands under irrigation, where drainage serves two purposes: to maintain a well aerated soil and to permit leaching.

For salinity control only, the depth of the watertable is relatively unimportant because the salt content of the soil is mainly determined by the prevailing direction of water movement through the soil rather than on the height of the watertable, although there can be a certain mutual influence. Table 1 is a sample of unpublished data on this subject which came to my knowledge.

As can be seen from some of the observations in this table, even though the watertable is deep, salinity can be high. Apparently, a scarcity of irrigation water, or another constraint, makes salinity control not feasible in these situations.

The growth factor salinity has received enormous attention in the last decades. The literature on the subject has been reviewed by BERNSTEIN (1974), who gives ample information on crop tolerance to salinity. Soils with ECe values of 4–8 are considered saline because the yields of most crops become negatively affected in this range. ECe values of 8–16 are so high that only salt tolerant crops yield satisfactorily (see article by van

Table 1.
22 Random observations of soil salinity in relation to watertable depth (based on unpublished data from Khairpur Demonstration Plots, Pakistan).

watertable depth (ft)					
EC_e*	<4	4–5	5–6	6–7	> 7
<4		1		1	7
4–6			2		3
6–8					2
8–10				1	1
10–12		1			
12–14					
14–16					1
16–18					
> 18			1		1

*electric conductivity of an extract of a saturated soil paste in mmho/cm; a value representing salt concentration proportionally.

Hoorn and van Aart in this book).

Nearly all the information available stems from experiments under controlled conditions, which means that it is not advisable to apply the research results directly to areas with management limitations. One cannot always predict yield increases merely on the basis of initial salinity figures and those one expects to obtain with a drainage cum-leaching program; one must also measure yields. This is illustrated in Figure 8, which shows yields obtained in the Khairpur Demonstration Plots.

Figure 8 reveals that yields in soils considered saline are not consistently less than yields in non-saline soils. Admittedly, so few data are available for EC values > 10 that no firm conclusion can be drawn. ALVA et al. (1976) reported that in Peru rice yields as high as 6400 kg/ha were observed on a soil with EC values of 16 mmho/cm in the top layer and even higher salinity values in the deeper layers.

Apparently crop response to salinity under controlled conditions differs from that under conditions where other farm management constraints are also present. The explanation must be the interactions between different growth factors and perhaps compensating circumstances. If one had had only the salinity figures of Table 1 and not the corresponding yields of Figure 8, one probably would have concluded that the soils needed leaching. But, because the low yields occur in non-saline soils, it is clear that other farm management deficiencies must first be tackled.

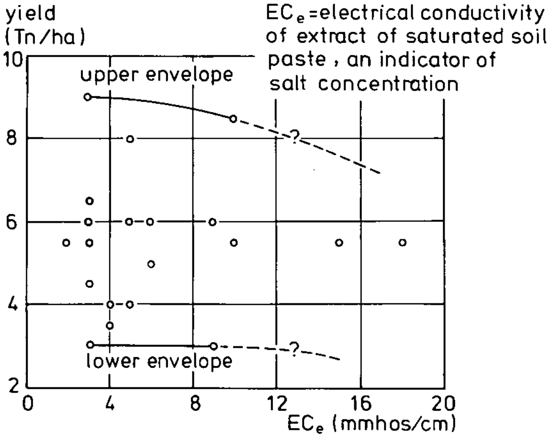


Figure 8.
Wheat production as a function of soil salinity (based on unpublished data from Khaipur Demonstration Plots, Pakistan).

To detect farm management problems field surveys of production functions are necessary. Theoretical deductions and rules of thumb are not enough. Nor should one consider isolated growth factors, but rather the complex of factors, including the possibilities of improving farm management.

Drainage and other factors

The relation between drainage and factors other than growth factors can be described very well on the basis of average water levels during certain (critical) periods. Exceptionally high levels appear to have limited influence, as will be seen in the following examples.

Soil stability

The increasing mechanization of farming, the desire to have more head of cattle per ha or to ensure timely farm operations such as sowing and harvesting have roused interest in the effect of drainage on the stability of the topsoil (its bearing capacity and workability). Most of the research on this subject has been done in the last decade (REEVE and FAUSEY 1974).

With a modification of the relations presented by WIND and BUITENDIJK (1979), Figure 9 shows the influence of watertable depth on workability. As the figure shows, the average depth of the watertable has a great impact on workability, especially in the range of 100–150 cm. It also shows that the q/h ratio (used in The Netherlands as a drainage criterion) exerts only a minor influence. From the point of view of workability it would appear that the average depth of the watertable is an excellent indicator and could serve as a good basis for a drainage criterion, the more so because it has proved to be a good indicator for plant growth too.

In pasture lands it is not the workability of the soil that is important but rather its resistance to poaching (trampling of the soil by the hoofs). It has been proved that drainage (both surface and subsurface) can prolong the number of grazing days and considerably reduce the damage caused by poaching (BERRYMAN 1975).

FAUSEY and SCHWAB (1969) studied the influence of drainage on timely farm operations. They found that the moisture content in the upper layer of a clay soil drained by surface drainage was 4–5 per cent higher throughout spring than that in a similar soil drained by subsurface drainage. Planting operations on the latter soil could start seventeen days earlier, which had important consequences for operation costs and yield levels.

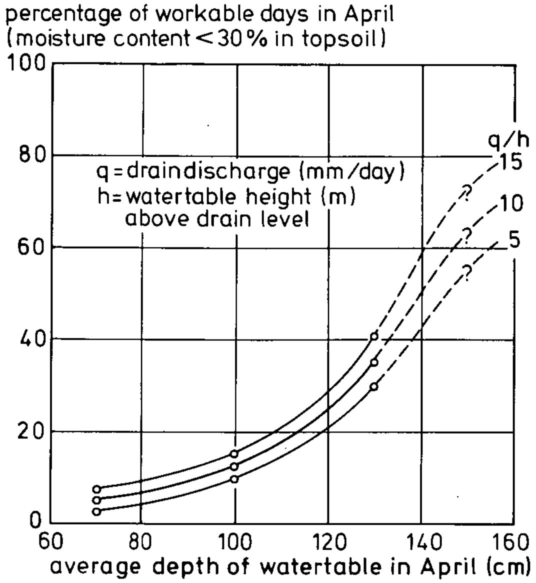


Figure 9.
Drainage and workability of a uniform silt loam soil under Dutch climatic conditions. Data obtained with a simulation model covering a period of 35 years (adapted from WIND and BUITENDIJK 1979).

It is to be expected that the influence of drainage on farm management potentiality will receive increasing attention in the years to come.

Subsidence

If groundwater is mined on a large scale e.g. for irrigation or for industrial or domestic water supplies, land may subside (BOUWER 1978). This will rarely happen as a result of drainage, except in peat soils or swamp land (SEGEREN and SMITS 1974). The results of a recent investigation on the shrinkage of peat soils are presented in Figure 10.
Although deep watertables may increase crop production on peat soils (cf. Figure 6) the adverse effect of shrinkage may lead to the decision that shallow watertables are preferable. Otherwise bridges, houses, or other structures may collapse. In tropical coastal lowlands, the disappearance of peat by oxidation and decomposition may lead to the appearance of underlying cat clays (potentially acid soils).

Hydrologic effects

Figure 11 depicts the different hydrological factors that may act on a piece of land. Here we can distinguish various interconnected reservoirs. As a result of drainage, the amount of water normally present in one or more of the reservoirs will reduce, thereby enlarging their storage capacity for additional water.
As is well known in hydrology, the buffering effect of larger storage capacities reduces outflows, especially peak outflows. Inflows, on the other hand, can increase. Therefore it is obvious that:

- with surface drainage, infiltration will reduce and the watertable will fall, although evapotranspiration may also reduce, which can lead to yield reductions (see article by Slabbers in this book)
- with subsurface drainage, infiltration and percolation can be more, hence surface drainage can be less (RYCROFT 1975)

The dependence of peak surface runoffs on the depth of the watertable has found recognition in The Netherlands in the equation of Blauw. This equation expresses runoff in terms of catchment area, frequency of exceedance, and a proportionality factor (F). For regions with a watertable below 1.7 m Blauw found that F = 1, whereas for regions where the watertable fluctuates between 0.0–0.4 m, F = 4. In the second case peak runoffs are four times higher than in the first.
Figure 12 illustrates another hydrologic influence that a small (20 ha) drainage project can exert on the surrounding land. After subsurface drainage had lowered the watertable in the pilot area, the net subsurface inflow (W–U, Figure 11, 12) increased and subsurface outflow (U) reduced (W is constant). In fact, the pilot area intercepted so much groundwater that the land between the pilot area and the sea changed from marshy land into well-drained land, which was promptly brought under cultivation by the local farmers.
The influence of drainage on the hydrology of a region is very much locally determined so no general guidelines can be presented. The development of calculation methods, however, is in full swing.

Conclusions

Despite the considerable research on the effects of drainage on agriculture, there exists a general feeling of dissatisfaction with the results of many drainage projects.
Van SCHILFGAARDE (1979) states that drainage criteria should be better defined, that the data base for crop response should be expanded and that drainage problems should be regarded as part of a total management scheme.
FOUND et al. (1976) conclude that a significant

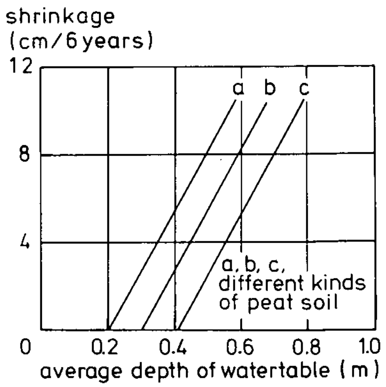


Figure 10.
Shrinkage of peat soils in The Netherlands can be related to average groundwater depth (SCHOTHORST 1978).

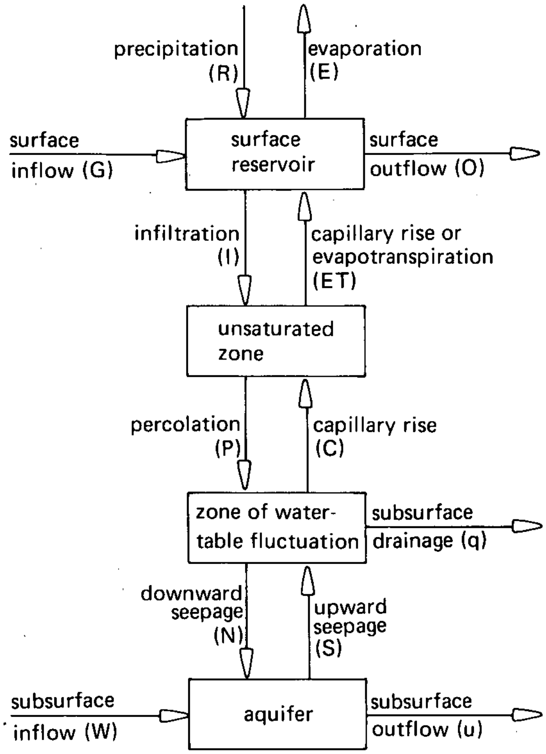


Figure 11.
Water balance factors in agriculture.

minority of drainage projects have failed to generate enough agricultural benefits to justify their construction. Further they consider that, despite the significance of drainage, little scientific analysis of the full effects has been undertaken. ZASLAVSKY (1979) calls for a new engineering approach. Otherwise the design of drainage projects will often be based on habits, superstitions, and prejudices, rather than on really measured and checked experiences.

When drainage design is based on a formula, with no consideration given to the environmental changes that can be brought about, failure may result. Figure 13 illustrates that an outfall drain, designed with the Manning formula, proved to be disastrous, not because Manning's equation is in correct, but because the drain drastically changed the hydrologic situation.

In most commercial, industrial, or public enterprises it is customary to make regular evaluations of past results. This rarely happens in agricultural water management projects, let alone in drainage projects. The lack of evaluation means that it is not known whether what was done was rightly done and that no information exists on how to do better.

The economic evaluation of a drainage system should include a great number of items such as:

- cost of the system
- increase in crop yields
- reduction of costs of farm operations and inputs
- gains obtained from timely farm operations
- profit, or damage, as a result of hydrologic side effects
- advantages of new cropping patterns
- social benefits accruing from intensified agriculture

This evaluation is no simple matter and can, of course, not be realised in the laboratory or in experimental fields, but requires regional surveys.

It has been shown in this article that our knowledge of drainage is detailed but fragmented, and that we have no integrated models with which to predict the beneficial and adverse effects of a drainage system. Drainage, therefore, is still a matter of trial and error, which means that monitoring of projects is indispensable. As drainage effects vary from place to place and form an intricate complex with other farm management practices, it is vital that theoretical considerations, book knowledge, and designs based on experience elsewhere be verified by extensive field observations and a proper statistical interpretation of the facts.

Reversely, only with sufficient evaluation data to hand will it be possible to improve existing theory and to extend our knowledge on the many

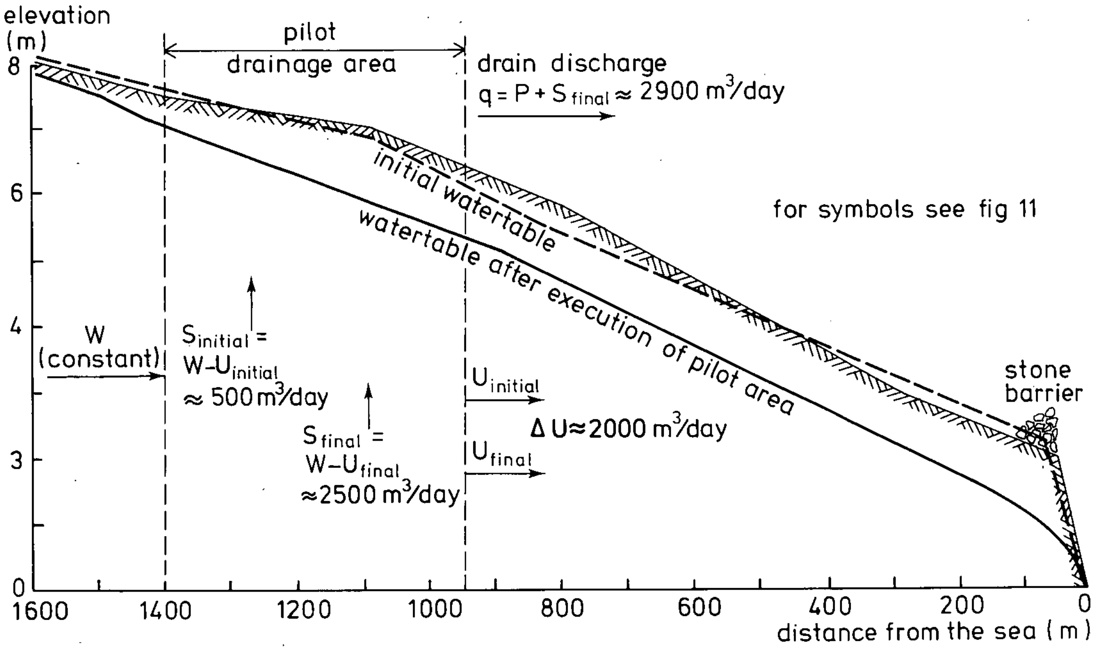


Figure 12.
A 20 ha pilot project area in a coastal valley in southern Peru (OOSTERBAAN 1975).

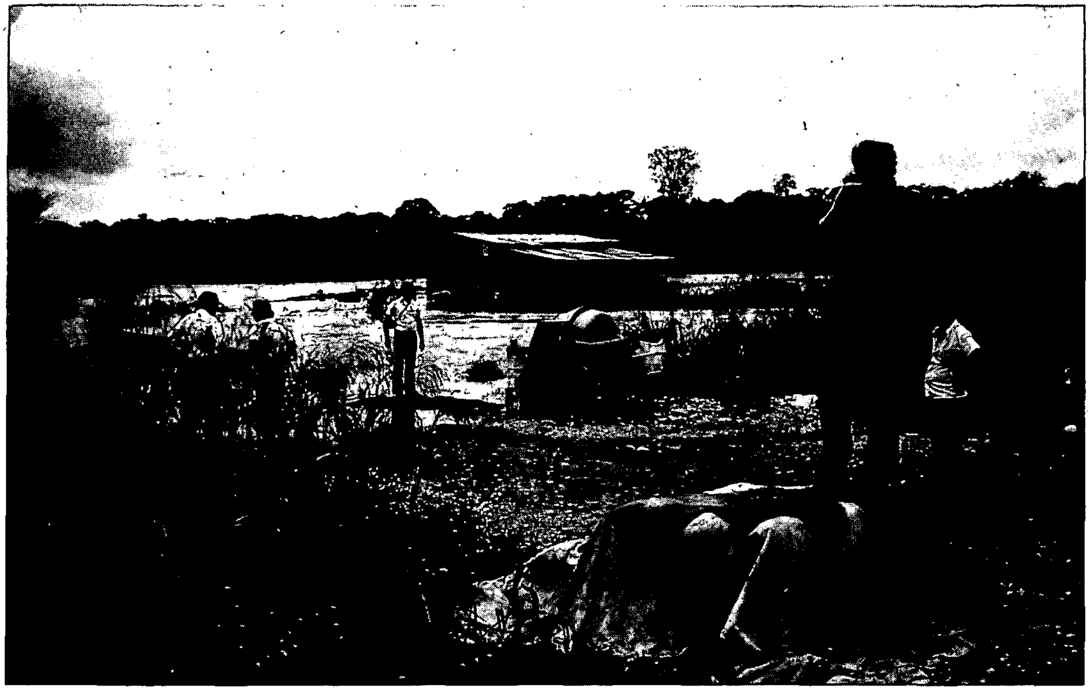


Figure 13.
What can happen to a drain if installed in an area prone to inundations.

interrelations between drainage and agriculture. Despite the need for them, monitoring programs will probably meet with a certain resistance before being established on a routine basis because:

- they are expensive, time-consuming, and labour-intensive
- the faith we have in our present design procedures is so great that the possibility of failure is considered a problem of second order
- monitoring programs may lead to the discovery of errors that can have serious political consequences
- there is a tendency to confine scientific work to the office premises, with its laboratories, experimental stations, and computer facilities.

However, with the world's growing demand for food, the evaluation of projects and a more intensive collection of data on the farm will soon be unavoidable. Examples of such evaluation projects in developing countries are the cooperative programs of the Colorado State University (U.S.A.) and the Water and Power Development Authority in Pakistan and of the interinstitutional Panel of Dutch and Egyptian organisations which are assisting the Drainage Research Institute (Ministry of Irrigation) in Egypt.

After all, it is likely that the cost of a monitoring program is much less than the damage afflicted by a wrong project, which might have been avoided with a proper survey of past experiences.

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Developments in subsurface drainage techniques

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Introduction

Subsurface drainage is the technique of controlling the watertable by means of almost horizontal systems of open-jointed or perforated pipes installed at a certain depth in the ground or by 'mole' drains, which are unlined circular channels constructed in the ground. Water flow in these artificial channels occurs by gravity.

The term subsurface drainage is used to differentiate it from surface drainage, which is the removal of excess water by shaping the land so as to make the water flow over the surface to furrows, ditches, or waterways. Ditches can also, to a certain extent, serve to control the watertable, but their use for this purpose is being superseded by underground drains because of such disadvantages as loss of land, hindrance for farming operations and overland traffic, and heavy maintenance requirements due to prolific weed growth or instability of banks. Their use is nowadays mostly restricted to the disposal and transport of water, and sometimes to its storage.

Subsurface drainage systems were first applied on a large scale in the temperate zones of the world, especially in North America, Europe, and the Soviet Union. In the last decades the technique has also been introduced in arid and semi-arid zones, in combination with the introduction or improvement of irrigated agriculture.

In Europe, until some 25 years ago, drains were laid exclusively by hand. The pipes used were short clay ware or concrete pipes. A narrow trench was dug, accurate to the required depth and grade (Figure 1), the last few centimetres of soil being removed with a gutter-shaped scoop to form a proper bedding for the pipes.

To avoid soil disturbance around the pipes, a man would stand beside the trench and use a hook with a long handle to lay the pipes.

Drain installation by hand required 230 to 300 manhours per 1000 m of drain and was thus very labour intensive. It is therefore not surprising that efforts were made to mechanize the installation of subsurface drains. Drain installation was first mechanized in the U.S.A. in the 1920's, but it was not until the 1950's that it was introduced in Europe.

The mechanization of drain pipe laying in The Netherlands was greatly promoted by a number of factors:

- the large expansion of new agricultural areas to be drained
- the need for larger field sizes and better trafficability required by the modernization of agriculture in areas poorly drained by ditches and furrows
- the steady increase of wages and the growing scarcity of experienced labour.

The introduction of machines for pipe drain installation led to the appearance of specialized drainage contractors, working on a price per unit basis and therefore keen to further improve the

Figure 1.
Subsurface drain installation by hand (1952).
(By courtesy of Government Service for Land and Water Use).

technique. We shall now briefly review these developments that took place in the last 25 years.

Drainage machines

Trencher drainage machines

The first drainage machine to be used successfully in The Netherlands was a Buckeye imported from the U.S.A. in 1954. It had an open digging wheel with scoops and a trench box with a shoe to shape the trench bottom. The pipes slid down a chute and were laid in position by a man standing on the machine or walking alongside. The trench was thus excavated entirely by the machine, but pipe laying was still largely manual. The application of cover material, if used, was a separate operation. With the machine an average capacity of 140 m drain per hour could be obtained.

In the mid-fifties some Howard digging wheel machines, imported from Britain, were also used. The chute was constructed in such a way that the pipes automatically slid into position as the machine moved forward. With these machines, which were smaller than the Buckeye, an average of 70 m drain per hour could be obtained. Their depth range, however, was not entirely adequate for Dutch conditions.

The first drainage machines manufactured in The Netherlands were built onto a farm tractor (Figure 2).

As experience was gained with these machines, it was found that they could excavate the trench and lay the pipes with as much accuracy as pipes laid by hand.

Within the next few years various improvements were incorporated (Figure 3):

- the digging wheel was replaced by a digging chain with knives, which allowed a lighter and more compact construction of the machine and resulted in higher laying capacities
- a hydraulic control system was applied to regulate the digging depth
- the machine was no longer built on to a tractor, but on a special frame provided with long and wide tracks.

By 1958, some 80 drainage machines were in use in The Netherlands. When clay tiles were laid by these machines at the usual depth of 1.2 m and the usual trench width of 20 to 25 cm, capacities of 250 to 300 m per hour were normal. A crew of

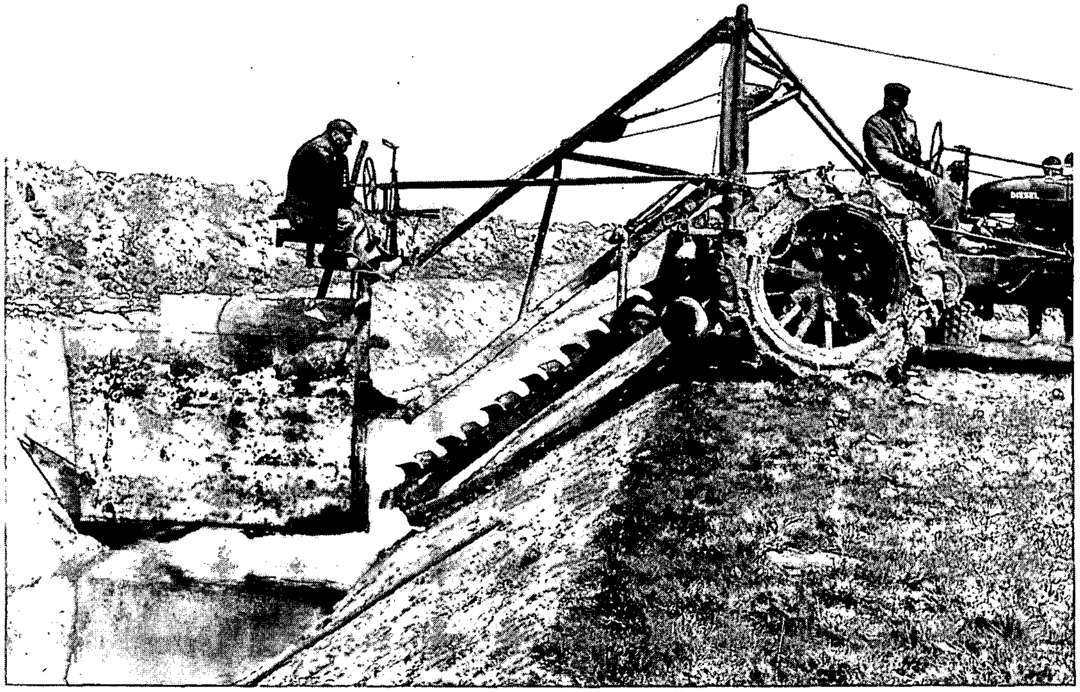


Figure 2.
Early model drainage machine (1958) using digging chain with knives (van den Ende).
(By courtesy of Government Service for Land and Water Use).

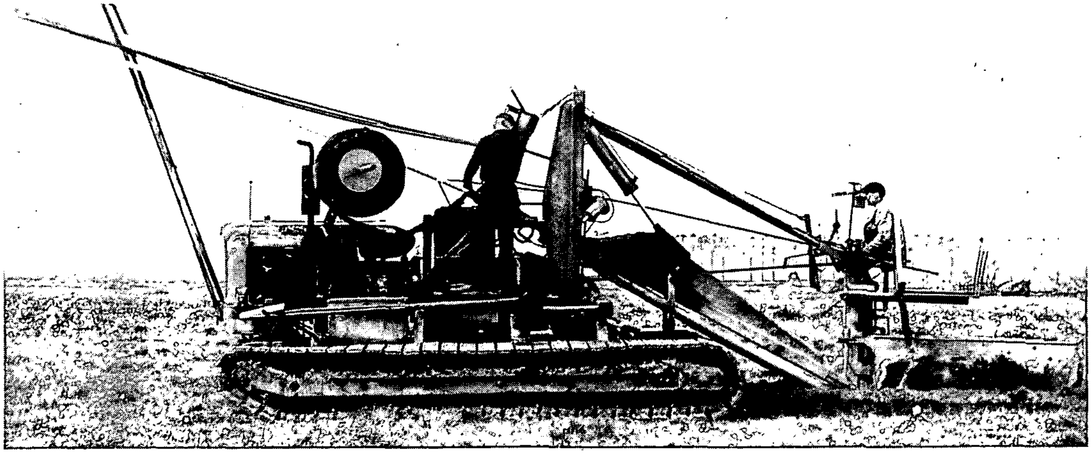
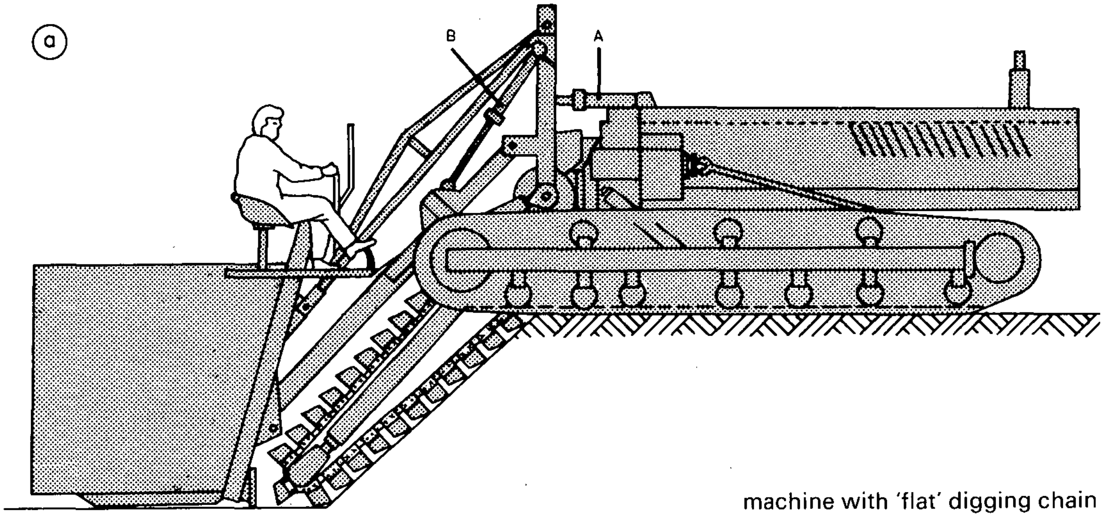
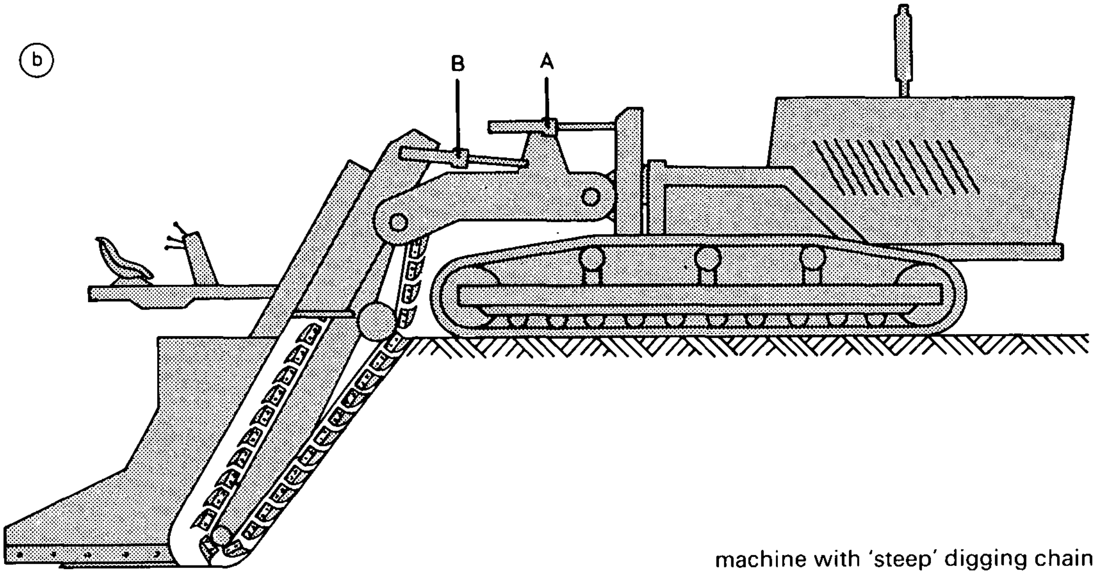


Figure 3.
Drainage machine installing smooth plastic pipe wrapped on the machine with peat litter band, 1967 (Draiëntie). Flat digging chain type, see also Figure 4a. (By courtesy of Government Service for Land and Water Use).

7 men was required for this operation so that the labour input was 25 to 30 manhours per 1000 m drain. These machines can be characterized as 'flat' digging chain type; they have the trench box connected to the machine frame by a parallelogram construction (Figure 4a).
With this system the angle of the digging beam varies according to the working depth. These machines are most efficient at working depths of up to 1.4 m in soft soils, which are the predominant conditions in The Netherlands.
The success of the drainage machines in The Netherlands led manufacturers to build machines for export as well. This greatly stimulated the adaptation of the machines for a wide range of working conditions: hard and stony soils, working depths of up to 2.5 m for arid irrigated lands, and the application of a gravel pack around the drain pipe. This led to the development of 'steep' digging chain type machines (Figures 4b and 5), which have the trench box connected to the machine chassis by an intermediate frame.
While trenching, the digging beam is at an approximately constant angle of 60° with the horizontal, irrespective of working depth. Other adaptations consisted of increased engine power up to 200 hp, adjustable width between the tracks (narrow for transport, wide for digging), and the track frames flexibly connected to the machine chassis for movement over uneven ground.



machine with 'flat' digging chain



machine with 'steep' digging chain

Figure 4.
Two main types of trencher drainage machines. Principle of depth regulation: while trenching, the shoe rests on trench bottom and the lifting cylinders A are in float position; depth is regulated by expanding or retracting cylinders B.

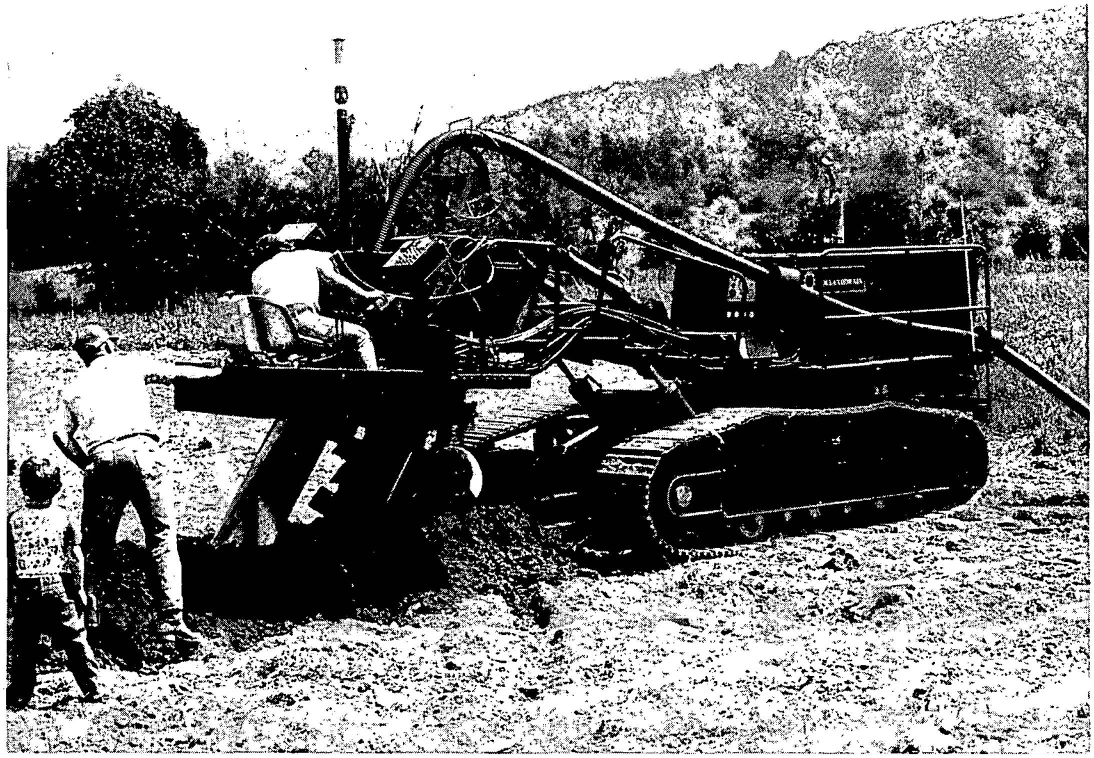


Figure 5.
Laser equipped drainage machine installing corrugated PE pipe, 1977 (U.S.A.). Steep digging chain type, see also Figure 4b. (By courtesy of Steenbergen Hollanddrain).

Trenchless drainage machines

An entirely different development is the trenchless drainage machine, also called drain plough. Trenchless drainage evolved from mole drainage, which is another form of subsurface drainage, although one not practised in The Netherlands. Mole drains are circular channels pulled in the soil by a mole plough. This technique is widely applied in heavy clay soils with a low hydraulic conductivity as, for example, in the United Kingdom (BAILEY 1979).

The invention of flexible drain pipe (which will be described later) made it possible to use the mole plough principle for pipe laying. With the trenchless machine a hollow blade is pulled through the ground and the drain pipe is guided into position through the blade. Several makes of trenchless machines are used in Europe, northeastern U.S.A. and Canada. The blade is manufactured as an attachment to a heavy crawler tractor or as an integral part of the drainage machine (Figure 6). On most types the working depth does not exceed 1.5 m.

The shape of the blade has been much improved in recent years. It is generally curved forward with a flat front so as to lift up the soil rather than push it aside, in order to create the space needed for the drain pipe and to reduce the traction required to pull the blade through the ground. The main advantage of the trenchless technique lies in its greater working speed and less wear and tear (fewer moving parts in the ground), and consequently a lower cost per metre of drain installed. Trenchless machines require a relatively dry topsoil for the crawler tracks to find enough grip to develop the high traction power to pull the blade through the ground. This requirement may limit the suitable working period for the trenchless machines. Some machines are equipped with winch traction to reduce slip.

The functioning of drains installed with the trenchless technique depends very much on the changes in soil structure brought about by the passing of the blade. Above a certain critical depth, heaving and fissuring of the soil takes place, but below that depth, deformation or compaction will occur. This may reduce the hydraulic conductivity of the soil in the vicinity of the drain pipe and hamper the entry of water. Further, because of the speed of installation, depth and grade control appears to be still a weak point. It is not yet clear under which conditions trenchless drainage is more favourable than drainage with a trenching machine (SPOOR 1979; REEVE 1979; NAARDING 1979; EGGELSMAN 1979; OLESON 1979; CROS et al. 1979).

Depth and grade control

The depth and grade of the drains laid by machine was initially controlled by means of sighting targets installed before the drain-laying operation was performed. The machine operator kept a sighting bar on the machine in line with the targets by moving the depth control switch as required.

In recent years, an automatic depth control system that makes use of a laser light beam has been introduced. This laser system, developed in the U.S.A., consists of a command post mounted on a tripod in the field and a receiver and control unit mounted on the machine. The command post emits a laser beam which is rotated in a plane that can be tilted according to the required drain gradient (STUDEBAKER 1971). When the laser beam hits the receiver unit at too low a point, the solenoid valve of the depth regulating cylinder is automatically actuated to make the machine dig deeper; when the beam hits at too high a point, the machine digs shallower.

With fast working trenchless machines, it may happen that the great inertia and friction forces cause a considerable delay between the signal of the receiver and the subsequent depth correction by the machine. This may lead to inaccurate drain gradients and even counter slopes. The result may be air entrapment in the drain pipe, causing it to function poorly. So far this phenomenon has received little attention and requires further investigation.

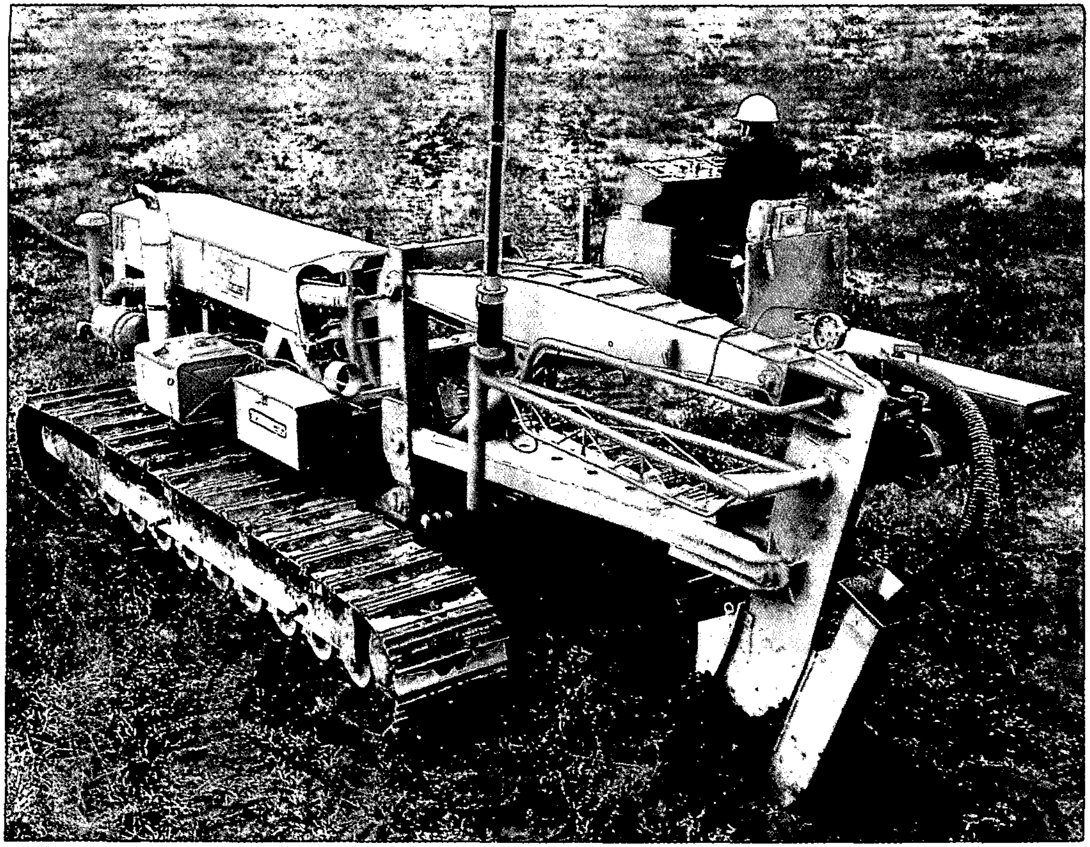


Figure 6.
Trenchless drainage machine, 1978 (U.S.A.).
(By courtesy of Barth Holland).

Drain pipes

Apart from the technical development of the drainage machines, the introduction of entirely new drainage materials has also contributed greatly to simplifying drainage operations, increasing installation capacities, and reducing costs. Whereas 25 years ago all subsurface drains in The Netherlands were made of either clay or concrete, these materials have now almost entirely been superseded by plastic.

The first experiments with thin-walled smooth plastic pipes started in 1959. They were of rigid polyvinylchloride with perforations in the form of longitudinal saw splits. Considerable research was done on required wall thickness, area of perforations, entry resistance for the flow of water into the pipes, and hydraulic capacity. The pipes were first applied in land drainage projects in 1960, and their use increased rapidly in subsequent years (van SOMEREN 1965; Figure 7). Their main advantage was the low weight per unit length, which greatly reduced the transport costs to the field and made transport in the field largely unnecessary because sufficient 6 m lengths of pipe for an entire drain line could be carried on the machine (see Figure 3). The simplified pipe handling meant that the machine crew could be reduced by two men, thereby lowering installation costs.

Since 1967 the smooth-walled plastic pipe has

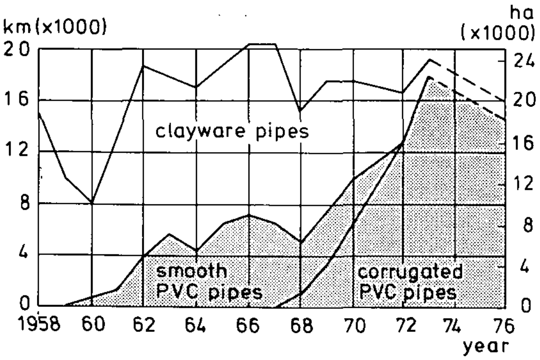


Figure 7.
Subsurface field drainage installed in The Netherlands, period 1958–1976.

gradually been replaced by corrugated PVC pipe. The corrugated form of the wall makes this pipe more resistant to deformation for the same quantity of PVC material, yet it remains flexible, which is a great advantage for pipe laying by machine. The corrugated PVC pipe, which has small perforations in the valleys of the corrugations, is manufactured in a series of diameters, ranging from 50 to 200 mm and is delivered in coils of different lengths. Individual lengths of corrugated pipe are joined by means of connecting sleeves of a screw type or with a few hooks that click behind the corrugations of two pipe ends, so that a strong connection can be made.

The introduction of corrugated plastic pipe has virtually eliminated the possibility of too open joints and misalignment of pipes. Installation by machine is very straightforward. Coils of the smaller-diameter pipe are usually carried on a reel on the machine and wound off as installation proceeds (see also Figure 12). The larger diameters are mostly laid out on the field and guided through the machine (see Figure 5). In The Netherlands, with a crew of 3 or 4 men, installation rates of about 600 m pipe per hour have become normal, resulting in a labour input of 4 to 7 manhours per 1000 m of drain.

In the U.S.A. plastic drain pipes are mostly of polyethylene (PE) instead of polyvinylchloride (PVC), largely because of the lower price and the ample availability of the raw material for PE in the early stages of development. Polyethylene has the advantage of preserving its quality at low temperatures, whereas PVC tends to get brittle and must be very carefully handled when temperatures are below 0 °C. A disadvantage of PE is that it has less stiffness than PVC so that it may lose its resistance to deformation when under pressure, especially in hot weather and when subjected to longitudinal stress. To minimize stretch of the pipe during installation some machines in the U.S.A., are fitted with a power feed mechanism to push the pipe into the pipe guide at the appropriate speed (JOHNSTON 1979).

Envelope materials

In the early subsurface drainage projects in Europe, the drains were often covered with a layer of organic materials to facilitate the inflow of groundwater and to prevent soil particles of the loose trench backfill from entering the pipes. The traditional materials used were sieved fibrous peat, wood chips, sawdust, straw from cereal crops, and heather bushes. The handling of these materials, however, was laborious, and the materials were not always available in the quantities required.

In its early days mechanical installation of drain pipes was not always successful, even though the drains were covered with the traditional materials. The poor results obtained were due to working under too wet soil conditions, installing drain pipes in new areas of unstable soils where no previous experience existed, and using plastic pipes whose outer diameter was small compared with that of the usual clay pipes. These problems initiated large-scale investigations in the laboratory, using model tanks, and in the field, making experiments with new organic and synthetic materials.

With the progressing mechanization of drainage work a search began for materials that could be produced in band form. A roll of such band could be carried on the machine and placed over the pipe during installation (see Figure 3). The first bands produced were made of the traditional organic materials: fibrous peat, flax straw, and later also coconut fibre. In the early sixties, a thin non-woven glass fibre sheeting was widely used. It was economical, and could easily be handled on the machine, to cover or even surround the pipes. Nowadays, however, its use is no longer recommended, except in some light-textured soils, as it tends to get clogged with fine soil particles and is very sensitive to choking by chemical or bacteriological deposits of iron compounds.

After the introduction of the corrugated plastic drain pipe, a technique was developed to prewrap these pipes with an envelope material in the factory. Prewrapping not only means great handling efficiency – the prewrapped pipe is coiled and installed through the machine in the same way as pipe without an envelope – but it also provides a complete mantle around the pipe. Since most of the groundwater enters a drain from below, the advantage of a complete envelope is obvious, the more so in soils whose stability is poor. The materials most used at present are coconut fibre and fibrous peat (Figure 8), but it is expected that the trend for further developments in envelope materials will move in the direction of synthetic fibre fabrics (KNOPS and DIERICKX 1979).

Even the proper selection of pipe and envelope materials does not always guarantee that the drains will function properly. Investigations in The Netherlands have convincingly proved that a decisive factor for successful subsurface drainage lies in favourable soil moisture conditions at the time of installation. Particularly detrimental is backfilling the excavated trench with soil that is wet because of a high watertable or because of rainfall during installation. If the soil structure in the vicinity of the drain deteriorates through smearing, kneading, compaction, or sedimentation, this will greatly hamper the flow of water into the drain. It is therefore advisable to install drains under relatively dry field conditions and when the watertable is below drain level.

A drain envelope is not required under all circumstances. Cohesive soils with a clay content of about 25 per cent or more present no stability problems and are not particularly sensitive to structural deterioration under wet laying conditions. Drains in such soils can be laid without an envelope (KNOPS et al. 1979).

In irrigated arid and semi-arid areas, coarse sand and gravel, found locally, is widely used as envelope material. If well graded from medium coarse sand to fine gravel, ranging in size from about 0.25 to 20mm, this material provides an effective and durable envelope. It is used in fine-sandy, silty, and dispersive soils, and in unstable subsoils, especially when the watertable is high.

In irrigated areas it is often not possible to select a favourable period for drain installation because the watertable tends to remain high throughout the year. In such circumstances, a gravel pack around the drain pipe is still the best way to prevent soil particles from being washed into the pipe immediately after installation. Because of the large quantities of gravel required and the high costs of transporting and handling this heavy material, a gravel envelope can constitute a substantial part of the total cost of drainage. The gravel is nowadays applied under and over the drain pipe through a hopper and ducts on the drainage machine. The handling of the gravel is often the limiting factor for the speed of the drain-laying operation, although this problem has been alleviated in recent years by the introduction of self-unloading gravel trailers. These fill a gravel hopper on the drainage machine which

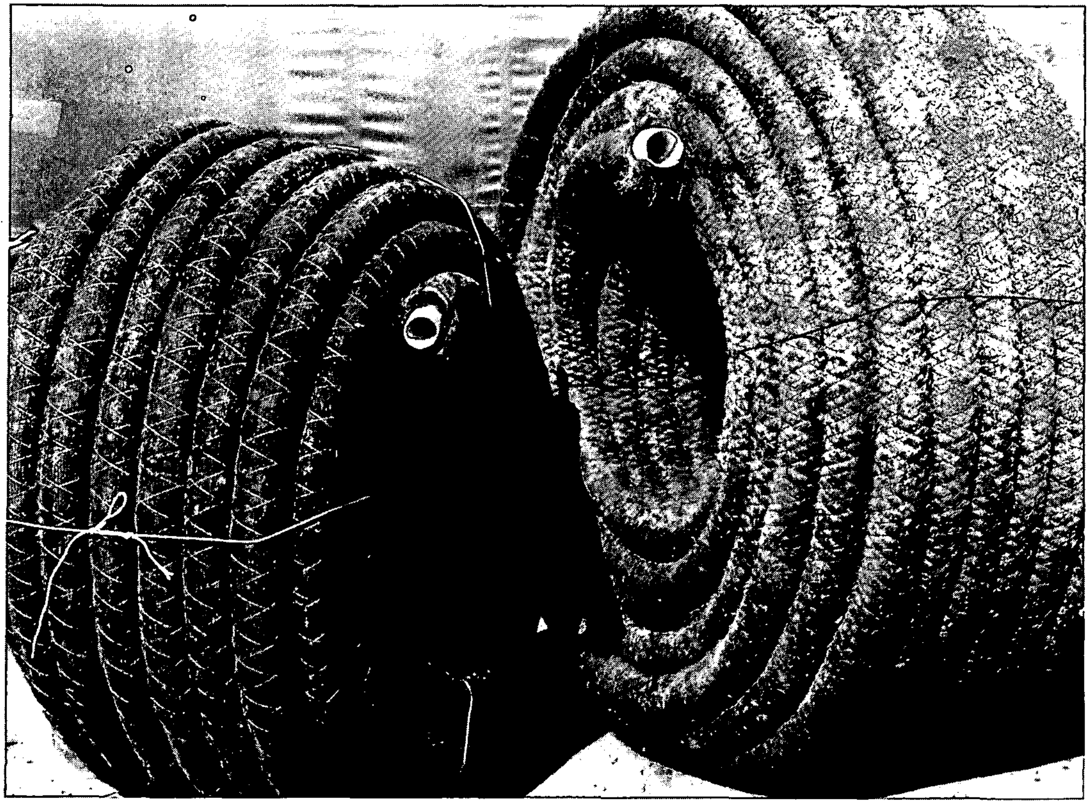


Figure 8.
Corrugated PVC drain pipe, prewrapped with fibrous peat (left) or coconut fibre (right).

Figure 9.
Drainage machine installing corrugated PVC pipe with gravel surround, 1977. Gravel supplied from self-unloading gravel trailer (Iraq). (By courtesy of Steenbergen Hollanddrain).

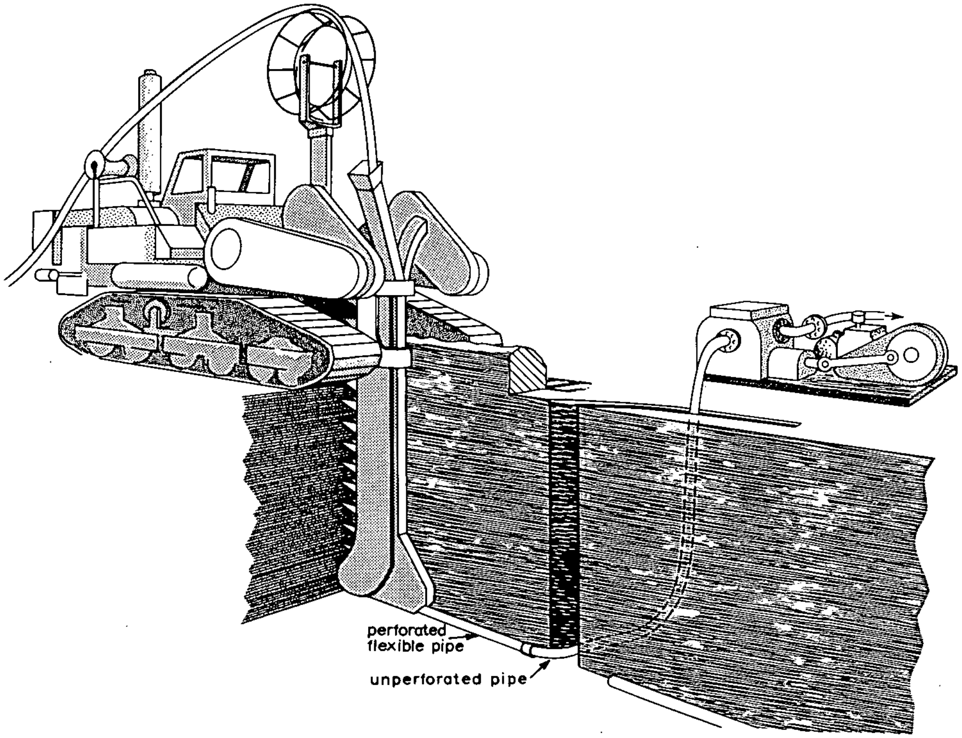
lays the pipe and applies the gravel at the same time (Figure 9).
A great deal of research on the textural requirements for gravel filters has been done in the U.S.A. (BOERS and van SOMEREN 1979).

Collector drain construction

The drainage system preferred in The Netherlands, as in other flat low-lying areas, is a singular system in which the individual pipe drains discharge into a ditch, the ditch acting as a collector drain that transports the water to a disposal point. Elsewhere, in arid and semi-arid areas under irrigation, but also in temperate humid areas where more slope is available, there is a tendency to install composite drainage systems, in which the pipe drains discharge into a collector pipe. Because of their large diameter, collector pipes are usually made of concrete, the price of large diameter plastic pipe not being competitive. They are installed with sealed joints, or are open jointed with a gravel surround. Under favourable soil conditions they can be installed with a heavy duty trenching machine in much the same way as ordinary pipe drains (Figure 10). When the size of the project does not warrant the use of a special machine, they are laid by hand in a trench that has been excavated either manually or by a multipurpose hydraulic backhoe excavator.
In unstable subsoils where 'quick' conditions arise due to a silty or fine sandy soil texture and a high watertable, serious difficulties are encountered in collector pipe laying. It is hardly possible to prepare a firm trench bottom and the trench walls do not stand up long enough to allow the pipes to be laid properly.
A new technique developed in The Netherlands in the last decade can overcome such problems. The technique, 'horizontal wellpointing', was initially developed for gas pipeline construction through high watertable areas to lower the watertable locally in a strip along the alignment of the pipeline. In this way the unstable 'quick' condition can be eliminated and the trench can be dug in the normal way. Of course, the use of this technique adds to the cost of the collector drain, but for really difficult situations there appears to be no acceptable alternative.
The technique consists of bringing into the ground a length of corrugated plastic drain pipe, prewrapped with a filter material and connected to a piece of blind pipe without perforations protruding above the ground. The blind pipe is connected to a vacuum piston pump that sucks up the water entering the perforated pipe, which thus functions as a horizontal well (Figure 11). The length of this pipe may vary from 30 to 80 m, depending on the depth below the original watertable and the hydraulic conductivity of the

Figure 10.
Heavy duty drainage machine installing concrete collector pipes, 1975 (Morocco). (By courtesy of Barth Holland).

Figure 11.
Principle of horizontal wellpointing technique for local lowering the watertable.



soil layers. It is usually installed at a depth of between 0.5 and 1 m below the bottom of the trench that is to be excavated.
The special machine used for this purpose has a vertical digging beam, around which the digging chain provided with scoops moves. At the rear side the chain moves downward between protecting side plates, preventing the soil from caving in. Immediately behind the digging chain the corrugated drain pipe is let down through a vertical guide tube, bending to the rear at the lower end. Machines are available that can install the horizontal wells to a depth of 6 m (Figure 12).

Outlook for the future

The technical developments in subsurface drain installation during the last 25 years have been spectacular. They have considerably increased the possibilities of installing drains in large areas of agricultural land within a relatively short time. They have also considerably reduced the labour input and have, as a result, kept the costs of subsurface drainage fairly stable, despite sharp rises in wages and costs of materials. In addition, they have enlarged the possibilities of applying mechanical pipe-laying in irrigated areas where deep drainage is required.
Clearly, developments have been very rapid, and not all the new materials and methods have been adequately investigated and tested before being

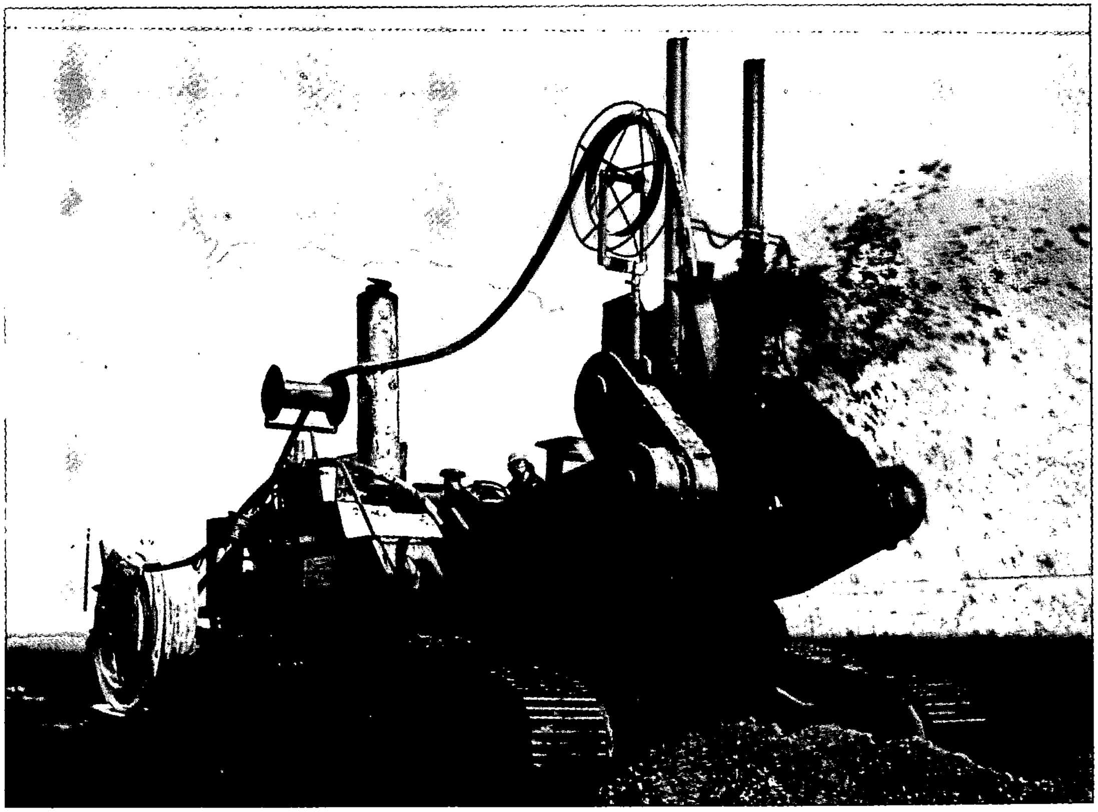


Figure 12.
Horizontal wellpointing machine, 1972. (By courtesy of Reinders-Wessemius).

applied in practice. The trenchless technique needs further perfection, especially with regard to grade control and functioning of the drains. Also the search for new envelope materials needs to be continued.

Nevertheless, it is also clear that subsurface drainage techniques are now available for a wide range of very different conditions. Nor is there any doubt about the need for drainage. FAO (1977), (see also DIELEMAN 1979) estimated that 52 million hectares of irrigated land in developing countries need to be drained in the 1975–1990 period and that some 26 million hectares of rainfed land will profit from the improvement or introduction of drainage. The total cost is estimated at US $ 14,000 million.

In the coming decades, the technique of subsurface drainage will have a vital role to play in increasing and restoring the productivity of agricultural land. In arid regions, it will constitute a key factor in the long-term viability of irrigated agriculture.

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Scientific information: transfer and retrieval

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Before the invention of the printing press, scientific manuscripts used to be copied in handwriting by monks. These copies found their way to libraries, where scientists, who were usually other monks, could consult them. This leisurely method of multiplying manuscripts came to an end with the advent of the printing press.

Today, the combination of sophisticated printing techniques and the worldwide acceleration of scientific progress is producing vast amounts of scientific information. One hears expressions describing this profuse production as 'the publication explosion' and 'the flood of literature'. In library circles, desperate attempts are being made to channel this great flow and to make its mass of information accessible. The process has become known as 'Operation Deluge'.

Obviously, the results of scientific research must be made available to those who need them. Needless duplication of research work can be prevented if scientists are aware of what other scientists working in similar fields are doing. But because of the great quantity of information being produced and the variety of ways in which it is published, a scientist faces a formidable task in keeping track of it all.

Growth of scientific information

Each year, the number of scientific publications increases by some 150,000. The present world total of scientific books is estimated at 100 million; that of journal articles at between 20 and 30 million.

An obvious trend in recent times is the preference being given to publishing scientific work in journals rather than in books, which seem to be following a tendency to summarize information already published elsewhere. Since the appearance of the first scientific journal in 1665 (*Journal des Sçavans*), there has been a prolific growth in this field. Figure 1 shows the spectacular development. From 1900 onwards, the number of scientific journals has been doubling every ten to fifteen years.

As early as 1830, the number of journals had grown so huge that the need was felt for abstract journals, the first of which was the *Pharmaceutische Zentralblatt*. These too have undergone a prolific growth, as is also shown in Figure 1. Figure 2 shows this growth in the single field of land and water.

Scientific congresses are also adding to the stream of literature, and their number too continues to increase. Considering international congresses only, of which 1000 were held in 1950, we find that their number had grown to 3500 by 1968. It is now estimated that some two million scientists attend such congresses each year. The papers they present are later published in congress proceedings.

In writing about the stream of scientific literature,

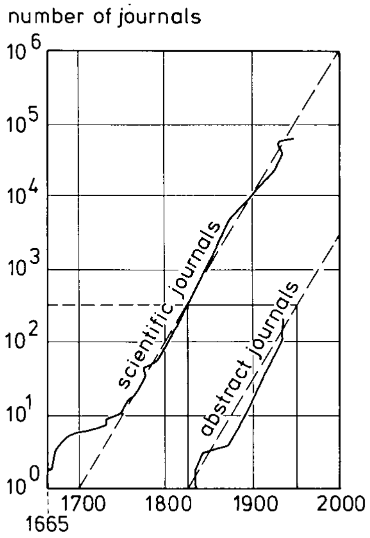


Figure 1.
Growth of scientific and abstract journals.

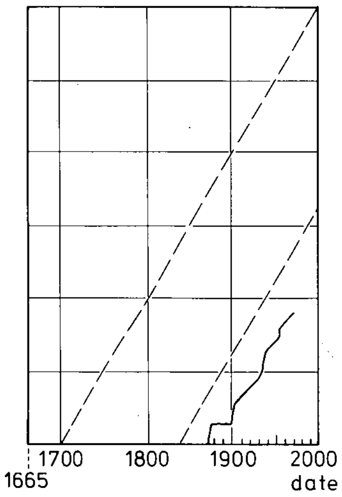


Figure 2.
Growth of abstract journals on land and water (based on data from WELLISH 1972).

MEADOWS (1974) rightly observed that there is a direct relation between the sums of money made available for research and the quantity of literature produced. As long as the funds budgeted for research continue to increase, we can expect that so too will the number of publications.

Structure of scientific information.

Van der WOLK (1968) defined information as 'knowledge in motion between people'. The present article treats 'documentary knowledge in motion between scientists'. The structure of this process is shown in Figure 3.

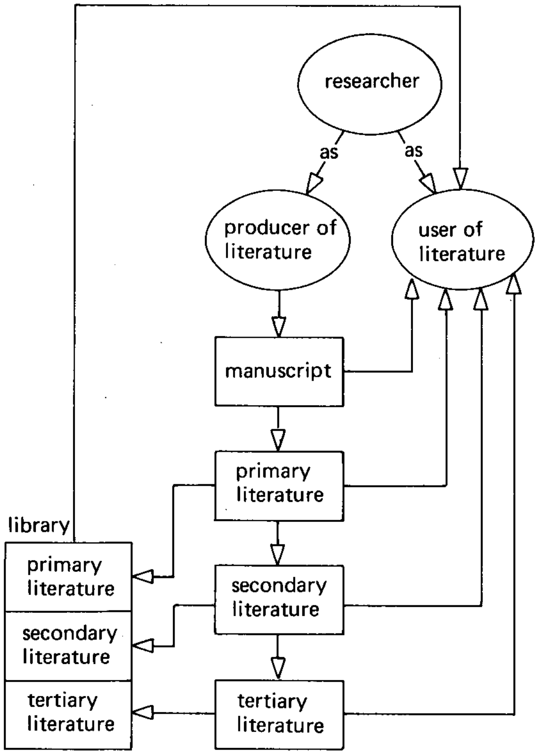


Figure 3.
Structure of transfer of documentary knowledge between scientists.

The manuscript produced by a scientist may become an article in a journal, a paper in the proceedings of a congress, or a book. All this is called primary literature. It is offered direct to the reader through his subscription to the journal or his purchase of the proceedings or the book. Or it may be offered indirectly to him through a library, where it can be retrieved by way of the catalogue. This applies to the entire book, to the congress proceedings in their totality, and to the journal as a whole. But it does not apply to individual chapters of the book, to individual papers in the proceedings, or to individual articles in the journal, which are 'lost' in the library catalogue. The 'loss' of these items has led to the creation of secondary literature, which treats the chapters, the papers, and the articles as separate publications. The original 'packaging' is undone and the items are 'repackaged' according to subject. Secondary literature is compiled by abstracting and indexing services. It constitutes a guide to the contents of primary literature. These guides are either kept in libraries or supplied direct to their potential users.
(Another type of secondary literature which does not enter this discussion is that intended as a register of all publications and aimed at 'Universal Bibliographic Control'. Examples are national bibliographies and publishers' catalogues).
Secondary literature, in its turn, can be retrieved through tertiary literature, which presents inventories of the abstract and indexing journals that are the guides to primary literature. Examples of tertiary literature in the field of land and water are the following:

- ABELL, L. F. 1978. Abstract Journals on Irrigation, Drainage, and Water Resources Engineering. Wageningen, ILRI
- GIEFER, G. J. 1976. Sources of Information in Water Resources. An annotated guide to printed materials. Port Washington, New York, Water Information Center
- RALSTON, V. H. 1975. Water Resources. A Bibliographic Guide to Reference Sources. Storrs, Un. of Connecticut. Institute of Water Resources.

Regulatory mechanisms

Obviously, not all the literature produced is equally valuable. Fortunately, however, to keep informed of developments in his field, a scientist need not read everything that is published. A number of regulatory mechanisms control the flow. These are:

Quality selection. At the start of this process, which comprises five sieves (see Figure 4), a manuscript either becomes a publication or it does not. Of the many that do, only a few finally remain as classical articles or books. After ten years, more than 98 per cent of scientific work is entirely forgotten.

Qualitative concentration. Four precepts describe the processes of qualitative concentration:

The 'star' system
A natural concentration of quality occurs among scientists, usually in the form of a 'school' headed by one or more of the leaders in a field. These 'stars' attract other 'stars' and the process of qualitative concentration continues. SLAMECKA and ZUNDE (1971) claim that n scientists will produce $\sqrt{n}$ 'stars'; or, from every 500 scientists, 22 'stars' will appear.

A ranking order of journals
The articles of 'star' scientists tend to be published in prestigious journals. Other authors working in the same field will then try to get their work published in the same journal. With greater numbers of manuscripts submitted for publication, the journal editors can afford to become ever more critical, selecting only the best articles. In this way a journal spirals upward in quality. It will be cited more frequently than others, will be more readily included in library collections, and will be consulted more often than journals not kept by the library. It is possible to rank journals in their order of relevance for a certain subject. Studies have shown that the product of the rank number and the citation frequency is constant. The highly-ranked journal *Nature* is cited 80,000 times a year, but the journal ranked 500th on the list is still cited 1,500 times a year.

Bradford's law
BRADFORD (1948) investigated the way in which articles on a certain subject are scattered over various types of journals. He discovered he could divide the journals into three categories, each of which contain one-third of the total of articles, as follows:
1/3 in a small number of specialized professional journals
1/3 in a much larger number of journals in related fields, and
1/3 in all other journals
The ratio of journals in each category is $1:m:m^2$ (m = approx. 5). So, if in one year 375 articles are published in 155 journals, 375 : 3 = 125 articles will be published in each category, with Category 1 covering 5 journals, Category 2 covering $5 \times 5 = 25$ journals, and Category 3 covering $5 \times 5^2 = 125$ journals (or one article in each journal).

The 80/20% rule.
This rule applies to many things. Dispensing chemists, for instance, have found that 80 per cent of the prescriptions they make up require the use of only 20 per cent of their range of stock. Similarly, librarians have found that 80 per cent of the requests they receive are for 20 per cent of the literature on their shelves. The rule also applies to scientific articles, 80 per cent of all articles on a subject being found in 20 per cent of the journals.

Barriers and losses

It would be ideal if a scientist could trace all the primary literature, arranged under subject, through the secondary literature. Unfortunately, barriers exist between the original material and the scientist, inevitably leading to losses. Some of the barriers are:

Incomplete coverage.
Not all publications can be traced because of:
- language barriers,
- the scatter of many subjects over many journals,
- deliberate omissions by editors of abstract journals, and

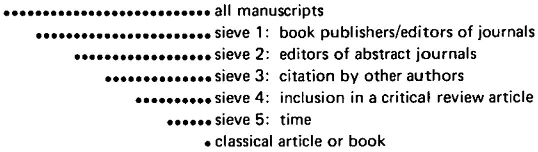


Figure 4.
The five sieves of quality selection (LOOSJES 1978).

- the time lag; the time between the publication of primary literature and its inclusion in secondary literature can vary from 3 weeks to 1.5 years.

Poor choice of key-word or classification code
Primary literature is registered in secondary literature by means of a classification code or key-word. If this is poorly chosen, the literature may be impossible to retrieve.

Problems in document procurement
Even when an interesting title is found, it is not always possible to procure the document itself.

Bibliographical aids

LOOSJES (1973; 1978) introduced the concept of scientific information in the form of a circle divided into three segments through which the information passes: (1) research, (2) the production of primary and secondary literature, and (3) the library. Each of these segments has its own bibliographical aids as shown in Figure 5.
The terminology used in this figure will be familiar to the reader, with two possible exceptions: 'current contents' and 'citation index'. Current contents is a publication that reproduces the list of contents of a selected group of journals. An example is *Current Contents of Agriculture, Biology, and Environmental Sciences*. For an explanation of 'citation index', see the next section of this article.

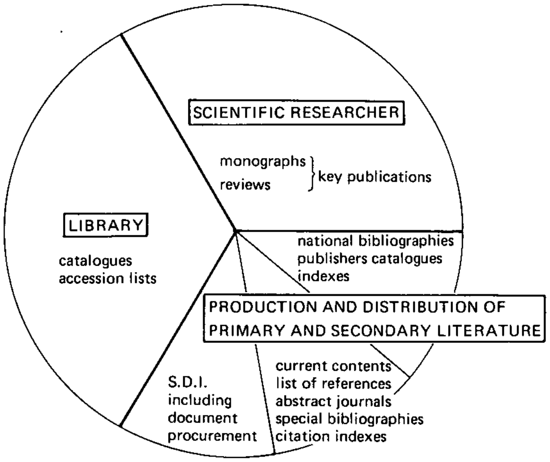


Figure 5.
The bibliographical aids in the various segments of the information process.

An excellent example of how scientists are being helped to cope with the literature explosion is the service provided by the United Kingdom's Commonwealth Agricultural Bureaux (CAB). Each year, under the very broad heading of agriculture, CAB's abstracting services searches through 8500 journals and an unknown number of books, annual reports, conference proceedings, theses, and government reports. Publications selected during this search are inserted, with their titles and an abstract of their contents, in one of the fifty abstract journals issued by the Bureaux, each covering one specialized section of agriculture.
In pre-computer days, the publishers of abstract journals confined their activities to collecting the material and distributing the product. Nowadays, their services have broadened considerably. Entries for future editions of abstract journals are now recorded on computer tapes. These tapes not only speed up the production of the journals at the time of printing, they also allow the information to be used in other ways, such as:

Repacking
An example of this is the following. Until 1975, there was no separate CAB abstract journal for irrigation and drainage, entries on these subjects being found in several of the other CAB journals. When the need for a separate abstract journal was recognized, it was then a simple matter to retrieve the entries on these subjects and re-issue them in *Irrigation and Drainage Abstracts*.

SDI (Selective Dissemination of Information):
This service informs scientists every month of the new literature in their field. For individual scientists, or for small groups, an 'interest profile' is compiled. This profile consists of key-words that indicate the subject in which the scientists are interested. Each month the profile is run off against the new information that has been fed into the computer, retrieving those titles that contain the key-words of the interest profile. If the profile fits a larger group, a current awareness bulletin may be issued.

On-line retrieval via a computer terminal
(For more details, see further in this article).
With all these new developments, libraries are being swamped by requests for literature, many of which they are unable to meet. To fill this void, some of the abstracting services will now provide photocopies of any of the literature they include on their lists.

The scientist as user

A scientist who is aware of the structure of information transfer may gather his information in one of the following ways:

Oral or written communication.
In choosing this informal way of information gathering, the scientist may be endeavouring to overcome the time-lag between the completion of a manuscript and its publication. Congresses and other such meetings also help to overcome this time-lag. For a simple item of information, a telephone call to a specialist may suffice.

The 'star' system
The scientist confines his search to 'star' journals, to the publication of a 'star' institute, or even to those of one 'star' scientist. In doing so, he will be applying the precepts of qualitative concentration described earlier. For a quick orientation in a field allied to his own, the 'star' method will suit his needs admirably.

Citation links, which can be used in two ways:
The snowball system.
The scientist begins by consulting one the most recent articles on his subject and then proceeds to consult the literature cited in its list of references. He repeats the process with the literature cited in those works, and so on. This is a very quick method of finding out what research is being done, where it is being done, and by whom. The scientist soon has an insight into the 'geography' of the research. Disadvantages of the method are that he is dependent on the thoroughness of the literature study made by the author of his original article, that literature in languages not familiar to that author are not likely to be included, and that the scientist moves back in time to older and older literature.

Citation indexes.
A citation index is an integrated search system that lists, under authors' names, the articles published in a selected group of journals in the preceding year, and the works cited in those articles. It comprises three separate but related parts: (1) a source index, which lists the citing authors, the titles of their articles, and the authors of the works they cite (2) a citation index, which lists the cited authors and titles, and (3) a subject index, in which the above material is arranged under subject. The Science Citation Index, for example, covers 2,200 journals that together publish some 22,000 issues annually and contain some 220,000 articles that cite some, 2,200,000 references.
Unlike the snowball system, in which the scientist moves backward in time, the citation index allows him to move forward from an early publication. For a historical review, or to find out what is happening in a particular field of research, the citation index is a valuable tool. It gives the user an excellent insight into the literature, although it will usually provide him with much that is irrelevant.

The systematic literature search.
Using the snowball method, the scientist will first try to find a critical review article in each major language. As these articles can be assumed to summarize the developments up to the time of their issue, the earlier literature can be ignored. The scientist then consults the relevant secondary literature of each language – if need be, locating it through the tertiary literature. For recent information, he consults back issues of appropriate journals over the last few years. Finally, he finds out what is happening at the forefront of research, either through guides to current research or through correspondence with the 'star' institutes that he

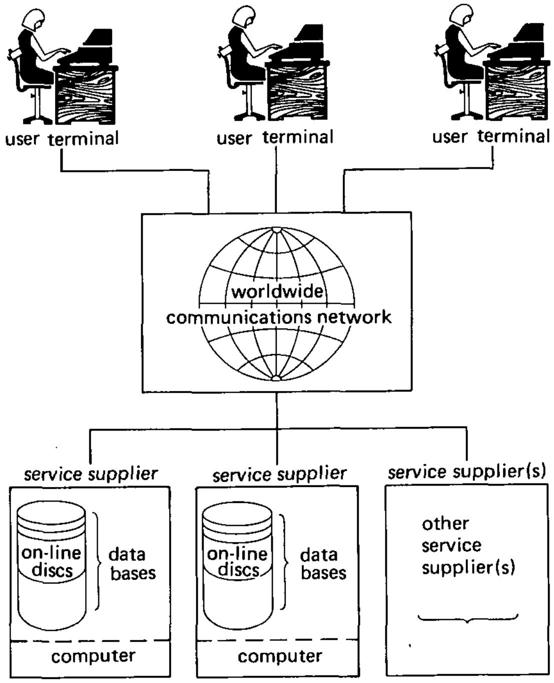
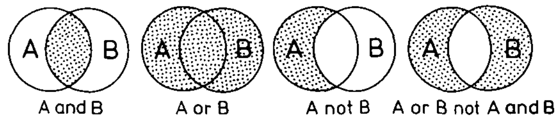


Figure 6. (page 187)
Via a worldwide communications network, the terminal-user links up with on-line systems.

Table 1.
Data bases that store bibliographical records on land and water.

Data base	Compiled by	Corresponding printed version	On-line systems
AGRICOLA, formerly CAIN	Nat. Agr. Libr. Beltsville,	Bibliography of Agriculture	BRS/DIALOG/ORBIT
AGRINDEX	FAO	Agrindex	IAEA
BIOSIS PREVIEW	Bio Sciences information	Biological Abstracts, Bio Research Index	BIOSIS/ESA-RECON/DIALOG
CAB ABSTRACTS	Commonwealth Agr. bureau	Soils and Fertilizers, Irrigation and Drainage Abstracts, Field Crop Abstracts, etc.	DIALOG
COMPENDEX	Engineering Index Inc. Un. Eng. Center,	Engineering Index	ESA/RECON ORBIT
Comprehensive dissertation abstracts	University Microfilms	Dissertation Abstracts Int. Am. Doctoral Dissertations	DIALOG/ORBIT
NTIS	Nat. Technical Information Service	None	DIALOG/ESA-RECON/ORBIT
PASCAL	Centre national de la Recherche Scientifique	Bulletin Signalétique No. 226: Hydrologic, geologic de l'ingénieur, etc.	ESA-RECON
SCISEARCH	Institute for Scientific Information	Current Contents Science Citation Index	ESA-RECON/DIALOG



A and B A or B A not B A or B not A and B

Figure 7.
The Boolean search operators presented in Venn diagrams.
A = set A: documents indexed under the term Drainage
B = set B: documents indexed under the term Heavy Clays

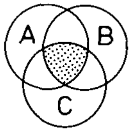


Figure 8.
Venn diagram for a search on drainage of heavy clays in relation to their workability.

has located via the 'geography' of the research. After completing a systematic literature search, a scientist will usually want to remain up to date. With the services nowadays offered by the computer, his chances of doing so are excellent.

On-line information retrieval

In the four methods of literature search described above, the scientist finds his information by leafing through books, journals, and library catalogues; he is conducting a 'manual' literature search. With the computer, much of this 'paper work' has been made superfluous. A scientist can now sit down in front of a computer terminal and – via a worldwide communications network – can link up with a host computer (an on-line system) that will supply him with the required information in a fraction of the time. (See Figure 6, page 185).
An on-line system (also known as service supplier) is a combination of a set of specially written computer programs and an operational computer that enables computer files (the 'data bases') to be consulted. HALL (1977) reports a total of 65 on-line systems, examples of which are BLAISE, DIALOG, and ORBIT.
An on-line bibliographical data base is a collection of records (usually derived from a machine-readable version of abstract journals) held online in a rapid-access computer store. Approximately 100 data bases store some 20 million unique bibliographical records, to which something like 3 million are added every year. Each record contains the author's name, the title of his work, an abstract, the place of publication, and keywords or classification code. In some cases a record may consist of actual data (e.g. chemical formulae) or texts (e.g. laws), but here we enter the province of data banks.
Contacts between terminals and on-line systems are made through communications networks such as TYMNET, TELENET, and the soon to become operational EURONET. Some of the data bases that store bibliographical records on land and water are listed in Table 1.

On-line searching: the Boolean logic.
Most on-line systems operate on the principe that is based on the logic of the 19th century mathematician, George Boole. It consists of three operators: AND, OR, and NOT. Figure 7 shows the principle as presented in diagrams developed by another mathematician, John Venn.
In the Venn diagrams, the area covered by Circle A represents the computer's complete set of references on a certain subject, say, Drainage. Circle B represents its complete set on another subject, say, Heavy Clays. These sets can be combined by means of the AND, OR, and NOT operators. The effect of the AND logic is to capture only those references that have been indexed under both Drainage and Heavy Clays.The result is titles of works on the drainage of heavy clays. Using the OR logic, the searcher captures references indexed under Drainage or under Heavy Clays, or indeed under both terms. The titles cover documents dealing with drainage, documents dealing with heavy clays, and documents dealing with drainage of heavy clays. The effect of the NOT logic is to capture all references on Drainage except those also containing the term Heavy Clays. The titles thus produced cover drainage, but exclude documents on the drainage of heavy clays.
It is possible to work with three or more circles, for instance, to obtain literature on the drainage of heavy clays in relation to their workability. With the computer's set of references on Workability contained in Circle C, the result obtained is represented by the small shaded part of Figure 8.

Cost of on-line retrieval.
The cost of on-line retrieval is made up of the following components:
- Systems operators' fees for data base acces. Of the 88 data bases reported by HALL (1977), the average cost per connecthour is $ 66, varying from $ 15 to $ 150
- The cost of the communications to the system(s) offering the data bases
- Cost of off-line printed citations
- Staff costs and cost of equipment and maintenance.

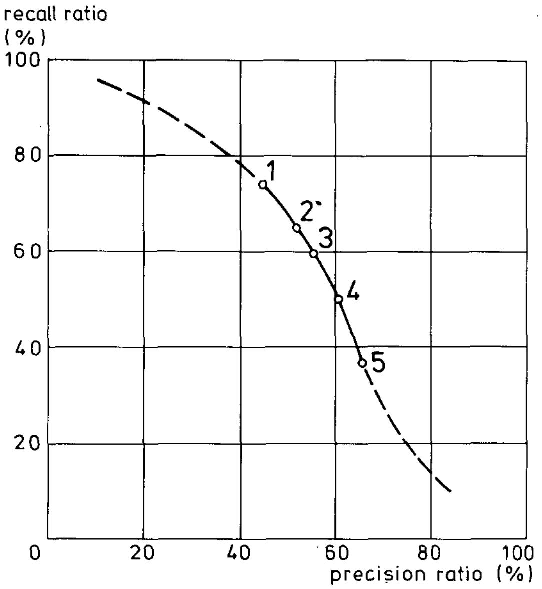


Figure 10.
Recall/Precision relation (LANCASTER 1968).

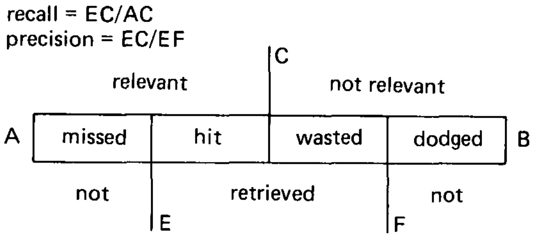


Figure 9.
Recall and Precision (VICKERY 1970).

Evaluation

To evaluate literature retrieval systems, CLEVERDON (1970) introduced two criteria: Recall and Precision. Recall is the number of relevant titles retrieved, expressed as a percentage of the total number of relevant titles present in the collection. Precision is the number of relevant titles expressed as a percentage of the total number of retrieved titles, including the extras, which he calls Noise.
VICKERY (1970) presents a similar idea in his clear and simple diagram (Figure 9).
The rectangle AB represents the entire collection of titles. For a particular query, Section AC is relevant, but the query, formulated in key-words, does not usually retrieve Section AC, but Section EF. Some of the retrieved titles (EC) are relevant, some (CF) are not relevant, and some of the relevant titles (AE) are missed. Any search divides the collection into four parts: Hit (EC), Missed (AE), Wasted (CF) and Dodged (FB).
Cleverdon's Recall translates into EC/AC in the Vickery diagram and his Precision into Vickery's EC/EF.
LANCASTER (1968) presented the relation between Recall and Precision as in Figure 10. Points 1, 2, 3, 4, and 5 represents the Recall/Precision performance with an increasingly refined search strategy and more and narrower descripters. The most refined strategy (5) will retrieve the fewest titles and will achieve the highest Precision but the lowest Recall. The somewhat less refined strategy (4) will retrieve more titles, thus improving Recall but reducing Precision. Similarly for 3, 2, and 1.

Viewdata and teletext

The on-line retrieval systems in use at present can only be consulted through terminals in libraries and documentation centres. Two new systems, however, are now making it possible to receive certain kinds of information in our own homes.
The first of these systems, VIEWDATA, was developed by the British Post Office. Any telephone subscriber who has his television set fitted with an adaptor can receive VIEWDATA transmissions on his TV screen. Via his telephone, which connects him with the VIEWDATA computer, he uses an numerical key-board to select from the information stored in the computer. The system is schematized in Figure 11.
The second system, TELETEXT, transmits information through a TV channel additional to the normal channels used for TV broadcasting. Its schema is shown in Figure 12.
With TELETEXT, one can select from the information offered, but cannot request specific information as with VIEWDATA.
It is reasonable to suppose that in the future scientists will be able to use systems as simple and convenient as VIEWDATA and TELETEXT keep themselves informed of new literature. Perhaps the literature itself will also be obtainable in this way because in sharp contrast to the rapidity with which titles can now be found is the wearisome path that the scientist must tread in obtaining the literature. Rising staff costs in every field of literature production and distribution are

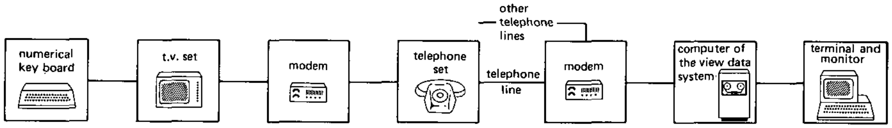


Figure 11.
Schematic representation of VIEWDATA.

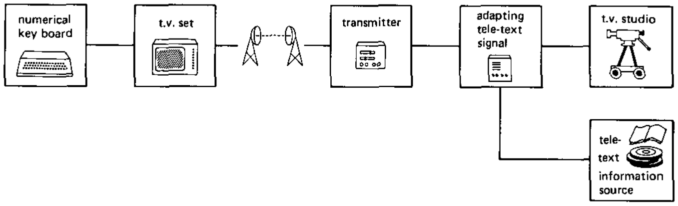


Figure 12.
Schematic representation of TELETEXT.

also working in favour of the computer. VIEWDATA and TELETEXT are new developments, not yet used on any wide scale. It is impossible to predict what their effects will be. Will they force books, journals, newspapers, even paper itself out of existence? The printing press once brought a dramatic change to society. Will it be replaced by an invention with an even profounder effect?

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