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WATER DEVELOPMENT FOR POWER AND IRRIGATION, THE ENVIRONMENT AND SUSTAINABLE DEVELOPMENT

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1 INTRODUCTION

Water development strategies are important for mankind because they afford flood control, irrigated agriculture and power generation. Water development policies also have pervasive repercussions on the natural environment. These ecological effects have only in recent decades received the scientific and, albeit to a lesser extent, the policy attention which they deserve. Appropriate water development policies are, therefore, a major area where environmental and development interests have to be reconciled for the sake of sustainable development for mankind.

The role of hydro-power in the energy sector has national and international ramifications. These relate to the overall growth of the energy sector as a largely supply-led industry, and the desirable mix between primary energy sources. Questions of global availability of energy resources for the long term are one major concern. The geopolitical significance of the location of such resources as oil and gas, the environmental effects of more widely available coal, and the political-strategic as well as environmental effects of nuclear power are other important concerns for global security and global development. All energy development policies have transnational effects on investment and trade, and on the 'global commons' through emissions and residuals disposal[1].

Investments in irrigation are important for national and global food supply and food security. However, they have important implications for different population groups and regions due to the privileged character of these investments. Those who can obtain access to more secure sources of water are 'lucky' compared to those who do not. This raises issues of internal trade and distribution of food between socio-economic groups and between food-surplus and food-deficit regions. Investments in irrigation have opportunity costs in terms of alternative, and conceivably less-privileged investments in agricultural development, leaving aside investments in non-agricultural sectors.

Investments in hydro-power and in irrigation are relatively immune to adverse short-term economic developments. These investments are usually well protected. Electric power generation is often seen as a precursor of development, and irrigation development is one of the most important instruments of infrastructure in facilitating or improving increased and more stable food production. Dams are, therefore, symbols of development. They

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1 Trends and problems of energy production, consumption and investment, and covering the second half of the 20th century have been reviewed in Aart van de Laar, *The Global Energy Crisis and International Development*, ISS Working Paper Series No 84, July 1990. They will not be discussed in the current paper. It suffices to note that pressures to develop new hydro-power will intensify, as environmental and strategic problems of alternative primary energy sources, coal and nuclear power, play an increasing role in strategic decision making. This holds true for conventional scenarios as well as for the more restrictive, demand-constrained rather than supply-led, NGO-initiated energy-future alternative.

constitute strategic investments in sectors and locations and, thereby, (re)structure rural society in water-scarce countries. Investments in dams shape irreversible development paths.

Because investments in hydro-power and irrigation development are large, the role of governments is usually crucial and multi-facetted. From developing the plans, to generating the needed resources, to allocating contracts, from changing water laws and pre-existing water rights, to determining conditions of access and use of the new resources made available. International investors, notably the international development banks, spend large resources on hydro power and irrigation development. There are powerful national and international networks and lobbies of industries, consultants and educational institutions such as universities, promoting investments in these sectors.

Increasingly, however, investments in dams are being criticised for technical, socio-economic, institutional and ecological reasons. The widespread and often retarded effects of large scale river impoundments and related investments in (re) shaping the natural environment are becoming more widely known. The outcome is a mixture of good and bad effects, leading sometimes to a reappraisal of the desirability of investments in dams. The rapidly increasing interference of Man in Nature has led to the emergence of 'stress ecology' as a relatively new focus of research which attempts to measure and evaluate the impact of natural or foreign perturbations on the structure and functioning of environmental systems and, potentially, on the management of these systems for Man's and Nature's benefit and survival. How then can Environment and Development in the words of the Brundtland Report (1987) be reconciled?

Moreover, irrigation investments following dam construction have often disappointed planners and investors as many of the expected benefits are not, or only much delayed, forthcoming, or are dissipated after relatively short periods of time.

Dams have become symbols of protest as well as symbols of development.

While a reappraisal of past investments leads to sometimes different judgements at present, additional problems have to be faced for the **future**. The number of proper dam sites is limited. More difficult topographic terrain limits the scope for additional irrigation development, or makes irrigation available at rising unit costs. With rapid population growth and generally increased pressures on natural resources, the opportunity costs of new investments are rising, and ecological as well as socio-economic effects of dam construction and related downstream investments call for more comprehensive planning than has been the case in the past.

New dam-related investments come on top of the growing need to rehabilitate and/or modernize past investments in these sectors and to overcome adverse effects of past investments which are only now becoming manifest.

1.1 Purpose of the paper

While recognizing that each river is different and that each irrigation system has special features, it is necessary and useful for social scientists to have a good grasp and understanding of general problems and issues in water development analysis and policy so as to **facilitate interface** discussions with technical (engineering and natural sciences) specialists. Much of the social science literature on rural development 'hangs in the air' as few attempts are made to bring together natural and social scientists more effectively to address the central question of why 'land managers' are so often unwilling or unable to prevent accelerated deterioration of the natural environment (Blaikie and Brookfield, 1987, xvii). Often the social science perspective is short term as fieldwork periods are short and an appropriate data base for long term trends for most developing countries is not available. There is, for instance, a vast literature on the effects of High Yielding Varieties on rural stratification, but there is much less social science literature on farmers' decision making in respect of water resources, the necessary though not sufficient condition for successful application of these same varieties. While much social science literature becomes dated rather quickly, references in the social science which attempt to deal with water development policy issues tend to remain valid and continue to be referred to, because once certain technical and institutional arrangements have been established, they tend to remain in force for considerable periods of time.

It is argued that long term trends in water resources availability and distribution are more important for rural societies than studying short term effects of introducing some new crop varieties. But to be able to study long term trends it is necessary for social scientists to have a clearer perspective on trends in natural resource development and use. Interface with natural scientists is therefore a necessity. Only if that interaction can be established will it be possible to also contemplate improved planning processes. Interaction with natural scientists and taking a longer term perspective of development might help to consider the environmental and longer term sustainability of development proposals. In such a perspective short term decision making could be reassessed as well, as the focus on long term trends tends to identify different issues and variables and mechanisms as important. In this connection of development planning, it has been said often but still bears repeating:

> *'that the planning procedures used by any particular party to the process are not defective in themselves, but that participants do not integrate (emphasis added) their professional activities according to an agreed conceptual understanding of the problems; that the criteria adopted at various stages in the planning process are not consistent; that the lessons to be gained from operating experience are denied; and that technological solutions cannot help overcome fundamental institutional problems.'* (Carruthers, in Widstrand, 1978, 302).

The purposes of the present paper are the following three: First, to present a number of general technical and environmental issues relating to the effects of dam construction and operations in concise form. Second, to then introduce major problems of technical irrigation development, with the purpose of raising issues for analysis by social scientists. The need for this arises as to many observers the irrigation sector is in crisis, both the long established systems in much of Asia and the generally more recently developed systems in Africa. Specifically, the present discussion focuses on basic problems in irrigation system operation, and on key elements for the socio-economic appraisal of investments in dams and in irrigation (taken together) through effects on human settlement and crop production, and on what may be termed the multiplicity of 'administrative arrangements' attending the development of such large infrastructure projects. Third, to discuss the often overlooked public health aspects of dams and related irrigation works, and possible engineering responses to overcome these important health risks.

Against this background a number of policy issues and problems in contemporary irrigation management, and rural development can be developed in subsequent paper(s), or shorter notes. The emphasis then changes more emphatically towards issues in which social science contributions, broadly defined, have been made over the last twenty years or so. Relevant issues are: the planning framework for irrigation development, system operation and management of main systems, efficiency and equity in water distribution, conflicting land and water rights, the scope for and impact of water user groups, irrigation finance for construction and maintenance, and irrigation 'turnover', which is the term used for privatisation of publicly built irrigation systems, to name the most important issues in the contemporary irrigation debate. More than in the present paper the emphasis will be on introducing a range of relevant literature[2].

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[2] Preliminary bibliographic work on many of these issues has already been undertaken, and a list of selected and, by now, available references are with the author. Of this current list of 200 items some 80 percent was not available at ISS before the present work started. Moreover, discussions have been initiated with members of the Irrigation Engineering Group at Wageningen University, to maintain and possibly promote the interface with engineering views on these issues. The need for this will be evident when it is realised that technical, administrative and/or economic policy measures may sometimes substitute for each other in irrigation design and operation. But in the disciplinary literature, such as economists writing about irrigation charges for promoting efficiency (see *World Development Report 1992*, World Bank) these linkages are not often explicitly recognised due to fragmentation amongst disciplines. In other words, the frame of reference for a number of disciplinary discussions is often inappropriate for specific irrigation situations.

2 TRENDS IN DAM CONSTRUCTION

The construction of dams has a long history. They were first constructed for the purpose of river regulation over 5000 years ago in Egypt; they had become popular in the Mediterranean area in Roman times, and were introduced into Western Europe with the overshot wheel during the late Middle Ages. One of the earliest large dams was the 27 meter high Tashahyan Dam on the Abang Xi, China, completed in AD 833, which is still being used for irrigation today. In Great Britain the first large structure was Coombs Dam which was not completed until 1787.

The era of major dam construction activity did not begin until the early 1900s and was coincident with changes in earth-moving and concrete technology (Petts, 1984, Chapter 1). During the past 50 years, most of the major rivers of the world have been impounded, at least to some degree. During the 1930s the construction of large dams and the grouping of multipurpose projects within entire river basins became symbols of the efficient application of engineering techniques to water management. Examples are the Tennessee Valley, USA, the Volga in the CIS (formerly USSR), and the Snowy Mountains Scheme in Australia.

However, the tide may be turning, for, by the mid-1970s it was noted that:

> *The great multipurpose dam which in mid-century was a symbol of social advancement and technological powers, came into bad odour........and was often attacked as destructive and poorly conceived' (cited in Petts, 1984, 3).*

Criticisms of the construction of large dams have come from environmental scientists, and there is growing awareness of the socio-economic consequences for population groups above and below newly constructed dams. Especially NGOs have become vocal and effective in mobilising public opinion against new dam construction, by focusing on governments and especially on the role of major international financiers such as the World Bank and other Regional Development Banks (Goldsmith & Hildyard, 1984).

The *World Register of Dams,* published by the International Commission on Large Dams in 1973, catalogues all structures more than 15 meters in height. By 1971 more than 12 000 had been built, impounding 4000 km3 of water and inundating an area of 800 000 km2. Summary information is provided in Fig. 1 (Goudie, 1990)

Before 1900, dam construction was increasing but numbers were small; between 1900 and 1945 there was a period of moderate building activity, separated by troughs associated with war and economic depression; and between 1945 and 1971 there was a period of accelerated impoundment with the completion of 8140 large dams world-wide. All regions experienced an extreme acceleration after 1950. The data exclude many dams in the former USSR but the most important omission is China. The world picture has been dominated since 1950 by North America, where over 200 major dams were completed each year between 1962 and 1968. Probably around 700 dams are now being built

Figure 1: The construction of dams

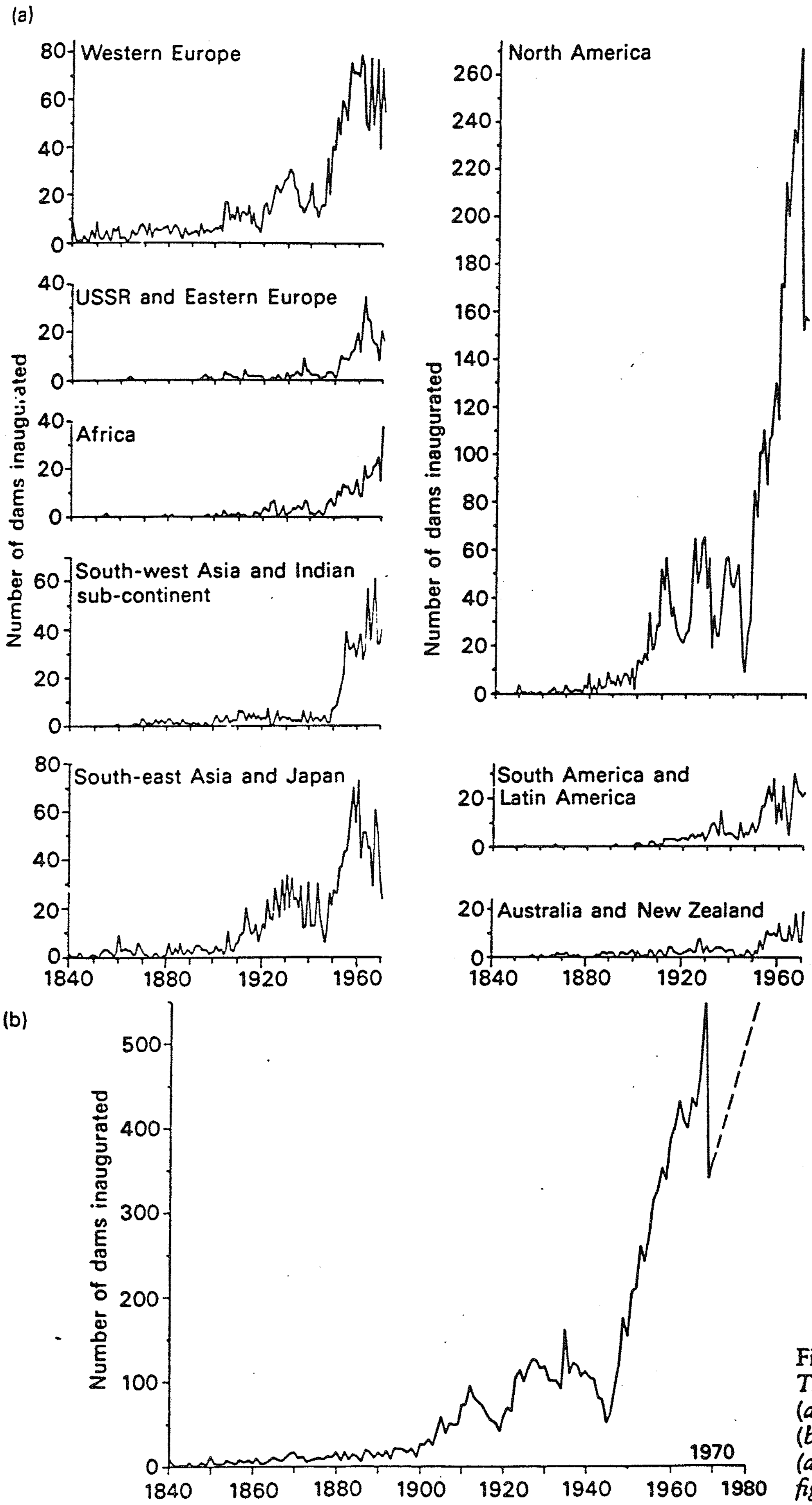


Figure ~~5.1~~
The construction of dams:
(a) for major regions
(b) for the world
(after Beaumont, 1978, figures 1 and 2)

Source: Andrew Goudie. The Human Impact on the Natural Environment. Oxford (Basil Blackwell), 1990.

annually worldwide, or more than two dams per day are being added to the world's rivers in attempts to enhance useable water resources. An update of the *Register* to cover the years 1971-74 demonstrated that the number of dams was being added to at a rate per year of 125 in the USA, 30 in Japan, 25 in China, 20 in India, 15 to 20 in Spain, 10 to 15 in Mexico, 10 in Australia, 8 to 10 in France, 5 to 10 in Korea, and 5 to 8 in Turkey. A second update reported increased dam-building activity during the last half of the 1970s in several countries, including Brazil, Argentina, India, Turkey and China. The major dams of the world are listed in Table 1; major dam-building projects that were due for completion by 1990 are given in Table 2, and a classification by region in Table 3 (Petts, 1984, 6-7-8).

In the 1930s the Hoover or Boulder Dam in the USA (221 m) was by far the tallest in the world. By the early 1980s it was exceeded in height by at least eighteen others. Of the eleven barrages over 5 km long only one, Fort Peck, USA, is more than 40 years old. A barrage at Kiev in the Ukraine is to be 41 km in length. Moreover, whereas Lake Mead, behind the Hoover Dam, was the largest man-made lake in the world in 1936 with 38 billion m3 of water, by the 1970s is was dwarfed. Zambia's Kariba Lake contained 160 billion m3, Aswan's Lake Nasser contained 157 billion m3, and Ghana's Akosombo 148 billion m3.

The areas inundated by large dams are very substantial (Table 4), with clear implications for the habitats of flora, fauna and for the population living in the dam lake areas. Where dam lakes are large and the area well populated (Table 20), the framework of analysis of impacts of dams and irrigation investments on settlements and on production will have to be widened substantially (see further Section 3.2).

As a result of river impoundment and the artificial storage of flood-water, the proportion of **stable run-off** has been augmented on every continent. Stable run-off in this context is defined as river flow resulting largely from ground-water discharge. (Table 5). In Africa and North America about 20 percent of the stable runoffs is contributed by impoundments, in Europe and Asia the figures are 15 and 14 percent, respectively, while rivers in South America (4.1%) and Australasia (6.1%) are least affected. However, on every continent the regulatory effects of man-made lakes upon the stream-flows exceed that of natural lakes by more than three times (Petts, 1984, 5). It has been suggested that by the year 2000, about two-thirds of the world's total stream-flow will be controlled by dams.

Table 1 Major world dams constructed before 1983. (Data from Mermel, 1982. Reproduced by permission of *Water, Power and Dam Construction*.)

A. Largest Reservoirs (threshold 65 × $10^9 m^3$)

Name	Completion date	Location	Reservoir capacity (× $10^9 m^3$)
Owen Falls	1954	Lake Victoria/River Nile, Uganda	204.8
Bratsk	1964	River Angara, USSR	169.3
High Aswan	1970	River Nile, Egypt	164.0
Kariba	1959	River Zambezi, Zimbabwe	160.4
Akosombo	1965	River Volta, Ghana	148.0
Daniel Johnson	1968	River Maniconagan, Canada	141.9
Bennett W.A.C.	1967	River Peace, Canada	74.3
Krasnoyarsk	1972	River Uenisei, USSR	73.3
Zeya	1975	River Zeya, USSR	68.4

B. Highest Dams (threshold 225 m)

Name	Completion date	Location	Dam height (m)
Grand Dixence	1962	River Dixence, Switzerland	285
Vaiont	1961	River Vaiont, Italy	262
Guavio	1982	R. Orinoco, Columbia	250
Mica	1973	River Columbia, Canada	245
Chicoasén	1981	River Grijalva, Mexico	245
Sayan-Shushensk	1980	River Yenisei, USSR	242
Mauvoisin	1957	Drange de Bagnes, Switzerland	237
Chivor	1975	River Bata, Columbia	237
Oroville	1968	River Feather, USA	235
Chirkei	1977	River Sulak, USSR	233
Bhakra	1963	River Sutlej, India	226

C. Largest Hydroelectric Power Dams (threshold 4000 MW)

Name	Completion date	Location	Planned power capacity (MW)
Grand Coulee	1942	River Columbia, USA	10 830*
Tucurui	1982	River Tocantins, Brazil	6480*
Sayano-Shushensk	1980	River Yenisei, USSR	6400
Krasnoyarsk	1972	River Yenisei, USSR	6000
La Grande 2	1982	River La Grande, Canada	5328
Churchill Falls	1971	River Churchill, Canada	5225
Bratsk	1964	River Angara, USSR	4600
Ust-Ilim	1980	River Angara, USSR	4500
Cabora Bassa	1974	RiverZambezi, Mozambique	4000

* The latest updatings have given corrected figures for the Planned rated capacity of Grand Coulee Dam as 5494 MW and of Tucurui as 8000 MW (Mermel, 1983).

Source: Petts, 1984, 6-8.

Table 2 Major world dams under construction and due for completion by 1990. (Data from Mermel, 1982. Reproduced by permission of *Water, Power and Dam Construction*.)

A. Large Reservoirs (threshold 65 × $10^9 m^3$)

Name	Completion date	Location	Reservoir capacity (× $10^9 m^3$)
Guri	1985	River Caroni, Venezuela	136

B. High Dams (threshold 225m)*

Name	Completion date	Location	Dam height (m)
Rogun	1985	River Vakhsh, USSR	325
Nurek	1985	River Vakhsh, USSR	300
Inguri	1985	River Inguri, USSR	272
Tehri	1990	River Bhagirathi, India	261
Kishaw	1985	River Tons, India	253
El Cajon	1985	River Humuya, Honduras	226

C. Hydroelectric Power Dams (threshold 4000 MW)

Name	Completion date	Year of initial operation	Location	Planned power capacity (MW)
Itaipu	1985	1983	River Paraná, Brazil/ Paraguay	12 600
Guri	1985	1968	River Caroni, Venezuela	10 000
Corpus Posadas	1988	1990	River Paraná, Argentina/Paraguay	6000
Yacreta-Apipe	1988	1986	River Paraná, Argentina/Paraguay	4050

* In the latest update, Mermel (1983) recorded that the Borocua Dam, Costa Rica, will be the fifth-highest dam when completed, at 267 m.

Source: Petts, 1984, 6-8.

Table 3 Global distribution of major dams and reservoirs.

A. Distribution by number (after Mermel, 1981. Reproduced by permission of *Water, Power and Dam Construction*):

	Completed to 1981			Dams under construction (109)*
	Large reservoirs (25)*	High Dams (24)*	Hydroelectric Power Dams (77)*	
NORTH AMERICA	4	6	21	14
USA	2	4	10	5
Canada	2	2	11	9
CENTRAL AND SOUTH AMERICA	1	2	11	25
AUSTRALIA AND NEW ZEALAND	0	0	0	1
SOUTH-EAST ASIA	1	0	6	10
Japan	0	0	4	4
China	1	0	2	6
SOUTH-WEST ASIA	0	1	0	12
India	0	1	0	5
AFRICA	5	0	1	5
EUROPE	0	5	2	6
USSR	9	3	9	8

B. Distribution of Large Dams in 1971 by storage capacity (%) Data from the *World Register of Dams* (International Commission on Large Dams, 1973):

	Storage capacity ($\times 10^6 m^3$)					Proportion of total (%)
	<1	1–10	10–100	100–1000	>1000	
NORTH AMERICA	24	34	23	14	5	38
CENTRAL AND SOUTH AMERICA	7	37	30	18	8	7
AUSTRALIA AND NEW ZEALAND	17	28	33	15	6	3
SOUTH-EAST ASIA†	61	23	12	3	1	18
SOUTH-WEST ASIA	9	40	34	14	3	10
AFRICA	26	34	26	11	3	3
EUROPE	24	37	27	11	1	20
USSR‡	40	24	35	1	–	1
Weighted averages§	28	34	24	11	3	
Weighted averages for reservoirs larger than 1×10^6 m^3		47	33	15	4	

* The number of cases considered from a listing by rank order.
† No data included for China.
‡ Limited data available.

Source: Petts, 1984, 6-8

Table 4. Areas inundated by selected dams.

Project	Country	Normal area of reservoir (thousand hectares)
Itaipu	Brazil/Paraquay	135
Tucurui	Brazil	216
Ilha Solteira	Brazil	120
Guri	Venezuela	328
Cabora Bassa	Mozambique	380
Furnas	Brazil	135
Aswan High	Egypt	400
Tres Marias	Brazil	105
Kariba	Zimbabwe/Zambia	510
Sobradinho	Brazil	450
Baibina	Brazil	124
Volta	Ghana	848
Brokopondo	Suriname	150

Source: E.Goldsmith and N. Hildyard, *The Social and Environmental Effects of Large Dams,* Wadebridge Ecological Centre. 1984.

Table 5. Stable river runoffs

Table 5. Stable river runoff (km^3) of the continents of the world

Continent	*Of underground origin*	*Regulated by lakes*	*Regulated by reservoirs*	*Total*	*Regulated by reservoirs as % of total*	*Total stable runoff as % of total runoff*
Europe	1 065	60	200	1325	15.1	43
Asia	3 410	35	560	4005	14.0	30
Africa	1 465	40	400	1905	21.0	45
North America	1 740	150	490	2380	20.6	40
South America	3 740	–	160	3900	4.1	38
Australasia	465	–	30	495	6.1	25

Source: after Beaumont, 1978

Source: Goudie, 1990, 156.

Part of the attraction of dams to policy makers is hydropower development, as has been noted above. The potential for hydropower development of different continents is large. By the early-1980s annual production as a percentage of potential output stood at 2.6% for Africa, 14.1% for Latin America and 17.8% for Asia, as against 61% for Europe and 78.5% for North America (cited in Goldsmith & Hildyard, 1984, 8). Between 1978 and 1989 the World Bank, a major source of external finance for power projets, appraised 119 energy projects of which 59 had hydropower components, and it approved $7,685 million financing for hydropower (Butcher, 1990, 2-3).

The prospect is therefore that natural rivers will become largely man-made industrial rivers, as the tendency has been to build bigger dams of larger capacity. Increasingly they have been designed to exert total control over the flow-regime downstream and to serve the multiple objectives of providing flood control, hydroelectric power and water-supply.

2.1 Effects of dams on the natural environment

Research on impounded rivers reflect the graph of dam-building activity. An examination of the citation structure of major publications (Fig 2) reveals that relatively few learned papers were published on impounded rivers prior to 1960, but a dramatic rise in the number of citations during the subsequent two decades is clearly shown. While a post-1950 growth of citations is common in science, as it relates to the general growth of scientific knowledge and the expansion of research groups and publishing outlets, the interest from the perspective of this paper is in the change in emphasis of such studies.

The framework in which Petts developed his book has implications for the choice of the categories of publications to be selected for Figure 2. They remain limited to hydrological and technical publications, widening to include studies on biological effects of dams. But work on social, demographic and economic aspects of dams is not included. Even so, some trends are interesting.

Obviously, pre-dam construction is dominated by engineering studies of suitable sites and of the technical intricacies of dam construction. Upon completion of dam construction early follow-up studies were mostly confined to channel degradation and reservoir sedimentation, and the studies related to questions of reservoir safety. From the 1950s attention shifted to include studies of fish migration and fish habitats, and spreading to riparian habitats in recent times. But the first major international symposium addressing the question of the environmental impacts of large dams upon the downstream river was not held until 1973 (11th International Congress on Large Dams, Madrid).

Figure 2: Growth of publications on impounded rivers

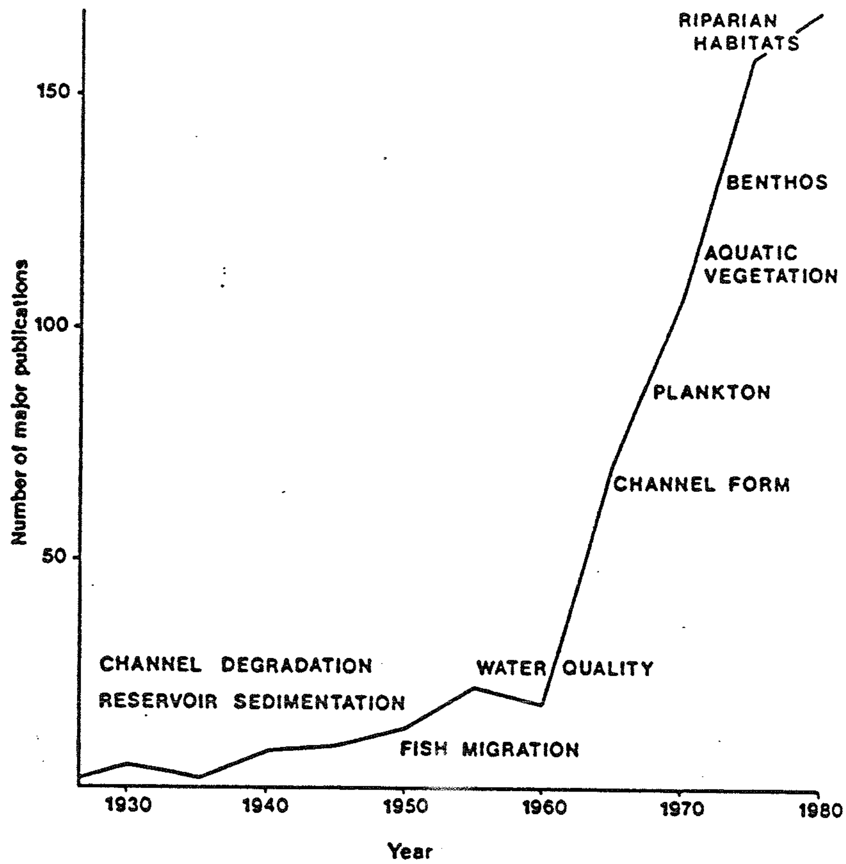


Fig. 2. The growth of major publications on impounded rivers. (Compiled by D. J. Gilvear.) The number of publications—excluding departmental, agency, or similar, reports—during each 5-years' period is shown, together with an indication of when specific themes first became important within this literature.

Source: Petts, 1984, 9.

For a fuller picture of the scientific literature on dams and related investments one should also include effects on (i) natural forests submerged in the dam lakes: as flora, and habitat for fauna, and for forest products of value to mankind such as foodstuffs, industrial materials or medicinal herbs, (ii) subsequent use of impounded river waters in irrigation: the effects on (net) agricultural production, on socio-economic differentiation, on involuntary resettlement of population groups and on water-related effects of irrigation on public health.

With this widening of research interests on primary and secondary effects of river impoundments, the range of disciplines involved also increases. Probable, on all these items the graph of an appropriate citation index will have the same shape. An early classic publication on the wider environmental effects of the activities of man (including, but not confined to river impoundments) is the volume by Farvar and Milton (1972). A decade later, much useful information on the social and environmental effects of large dams was compiled and made more widely accessible in Goldsmith and Hildyard (1984).

A general characteristic of much of the existing literature, whether in the narrow framework of dams and rivers or the wider range to include secondary water uses in irrigation, is that the interests of many individual scientists have usually been quite narrow - in part a reflection of the history of each separate discipline. This makes it often difficult to interrelate problems, issues and approaches, though that is evidently much needed. Taking a wider perspective, the goals, objectives and criteria for water development policies are more differentiated. This leads to increasing complexity in the analyses needed and to increasing risks of contradictory conclusions amongst facet studies and between disciplinary viewpoints. These have to be appropriately weighted and compared, when a more holistic view is taken of water development policy. However, there is a growing risk of (policy) paralysis through (too much) analysis. The realization of the growing complexity of the effects of dams, therefore, calls for an appropriate **planning framework**.

Unfortunately, the cumulative impact of the widening range of studies has not, so far, led to more integrated planning processes. The thrust is for 'improved' responsive approaches - for the control of impacts **after** dam construction, rather than through **anticipatory** evaluations of possible or probable impacts. A long-range and comprehensive planning approach is commonly rejected or ignored because of constraints of uncertainty which lie between the present and the future. Furthermore, many of the changes experienced by impounded rivers are caused not by the dam itself, but by agricultural and industrial/urban development stimulated by the provision of a reliable water or power supply, or of flood control (Petts, 1984, 13). Consequently, emerging problems have to be faced up to later in time, and, in most cases, by agencies other than those directly involved in, or responsible for dam construction.

All these forces point in the direction of a sequential approach to planning, whereby the starting point is a **project** framework around a suitable location for a dam to be constructed, rather than a **river basin** framework. In such a project framework the engineering point of view remains dominant in both the formulation and the examination of large dam projects. The planning sequence is then from project to utilization, and not from identified overall developmental needs to a strategy and projects to meet these needs. The customary project approach therefore precludes the development of a broader framework of analysis involving the development of options for water and land-use implications for the whole watershed, and to provide a basic prior justification for a development strategy. In a chosen strategy a large dam project may or may not feature prominently if options exist for a multitude of smaller scale development and water use options.

Apart from the analytical problem to effectively link up different scientific perspectives on dams and irrigation development in a more comprehensive planning framework, one should also not underestimate the political complexity of even attempting to develop a broader-based development strategy within the confines of a river basin. Proposals for river basin development have such long-lasting and profound consequences that the very suggestion of such developments will involve political action at local, state, federal, national and international levels.

The Narmada Valley Project, in India, illustrates these pressures and its consequences. The Narmada river, with a length of 1300 km, is the largest and least utilized major river remaining in India, and pressures for its development have intensified in view of the increasing overall water shortages expected in the near future (see section 3.1.2). According to the Central Water Commission practically the entire utilisable water resources in India will be actually needed by 2025 (cited in Iyer, 1989, A-106; see also Tables 19-20).

The Narmada project was intensively discussed in terms of a heroic and eye-catching development effort since 1946. As the Narmada River passes through three Indian states (Madhya Pradesh, Gujarat and Maharashtra), it was inevitable that it became the subject of a major interstate dispute, where each state attempted to prove that it had the greatest potential for development and thus deserved a relatively larger share of the waters to be diverted and to be used. Eventually, the number of proposed projects reached some 3200 dams, which would take more than 100 years to build if all these plans were to be taken seriously. To resolve the dispute, the Central Government set up a Tribunal in 1969 which took ten years to announce a decision. In the process all interested parties could use all available means to overstate their case, to deliberately underplay possibly negative effects and to suppress unwelcome dissent (Alvares and Billorey, 1987). In the end a decision was made in 1987 by the Central Cabinet to built two relatively large dams: The Sardar Sarovar and the Narmada Sagar. The World Bank is heavily involved in the Sardar Sarovar Dam and the construction of a 450 km main canal for drinking water and irrigation. In 1985 it approved credits of $450 million, or some 15 percent of total project cost. The project has come under intense criticism again during implementation. An Independent Commission, led by Bradford Morse, the former UNDP Administrator, strongly criticised both the Indian Government and the World Bank for the gross neglect of the ecological and social effects. In response, the World Bank Executive Directors decided in late 1992 to give India and the World Bank staff six months to do their homework better, and to take appropriate corrective planning action. (Internationale Samenwerking, December 1992). But of course, the Narmada case study as it evolves could also be used to illustrate the dilemma in major aid assisted projects: one stays involved to try to improve the project, if one withdraws the project may be completed anyway given socio-political forces in India and the fact that India pays the bulk from own resources.

In this paper we will not discuss existing or more appropriate planning processes for dam construction or river basin development. Rather, we would wish to focus on the nature and the importance of what until recently were much neglected aspects of water resource development policies. Interest is in the substantive issues involved.

We shall 'follow' the process of dam construction to then broaden the discussion to issues of secondary water uses in irrigation. We shall first discuss problems of direct physical impacts of dams. Important environmental consequences relate to such issues as earthquake triggering, increasing risks of floods, changes in sedimentation patterns, water poisoning through eutrophication mostly in Section 2, changes in ground-water levels, the build-up of soil salinity, water-logging in Section 3.1 and the transmission and expansion in the range of organisms affecting public health in Section 4. Socio-economic aspects will be taken up in Section 3.2 and again in Public health aspects in Section 4 of this paper.

2.1.1 Induced seismicity

It has only recently been recognised that the pressures applied to often fragile geological structures by the vast mass of water impounded by a big dam can - and often does - give rise to earthquakes (Goldsmith & Hildyard, 1984, 106-19). At least 7 cases have been reported of induced earthquakes with an intensity of 5 or more on the Richter scale (Table 6).

Detailed monitoring has shown that earthquake clusters occur in the vicinity of some dams after their reservoirs have been filled, whereas before construction activity was less clustered and less frequent. Similarly, there is a linear correlation between the storage level in the reservoir and the logarithm of the frequency of shocks (Goudie, 1990, 258). One reason why dams induce earthquakes involves the hydro-isostatic pressure exerted by the mass of the water impounded in the reservoir, together with changes in the pressures across the contact surfaces of faults. Paradoxically, there are some possible examples of reduced seismic activity induced by reservoirs. One possible explanation of

Table 6: Reservoir-induced changes in seismicity

Dam name	*Location*	*Height of dam (m)*	*Volume of reservoir (.10⁶ m³)*	*Year of impounding*	*Year of largest earthquake*	*Magnitude or intensity*
Major induced earthquakes						
Koyna	India	103	2780	1964	1967	6.5
Kremasta	Greece	165	4750	1965	1966	6.3
Hsinfengkiang	China	105	10500	1959	1962	6.1
Oroville*	U.S.A. (Calif.)	236	4295	1968	1975	5.9
Kariba	Rhodesia	128	160368	1959	1963	5.8
Hoover	U.S.A. (Ariz.)	221	36703	1936	1939	5.0
Marathon	Greece	63	41	1930	1938	5.0
Minor induced earthquakes						
Benmore	New Zealand	118	2100	1965	1966	5.0
Monteynard	France	155	240	1962	1963	4.9
Kurobe	Japan	186	199	1960	1961	4.9
Bajina-Basta	Yugoslavia	89	340	1966	1967	4.5 - 5.0
Nurek	U.S.S.R.	317	10400	1969	1972	4.5
Clark Hill	U.S.A. (S.C.)	67	2500	1952	1974	4.3
Talbingo	Australia	162	921	1971	1972	3.5
Keban	Turkey	207	31000	1973	1974	3.5
Jocassee	U.S.A. (S.C.)	133	1430	1972	1975	3.2
Vajont	Italy	261	61	1961	1963	
Grandval	France	88	292	1959	1963	V
Canalles	Spain	150	678	1960	1962	V
Changes in micro-earthquake activity						
Kamafusa	Japan	46	45	1970		2.5
Pieve de Cadore	Italy	112	68	1949		2.0
Grancarevo	Yugoslavia	123	1280	1967		1.0 - 2.0
Hendrik-Verwoerd	S. Africa	88	5954	1970		2.0
Schlegeis	Austria	130	129	1971		0.0
Transient changes in seismicity						
Oued Fodda	Algeria	101	228	1932		
Camarilles	Spain	44	40	1960	1961	3.5
Piasta	Italy	93	13	1965	1966	VI - VII
Vouglans	France	130	605	1968	1971	4.5
Contra	Switzerland	220	86	1965	1965	
Decreased activity						
Tarbela	Pakistan	143	13687	1974		
Flaming Gorge	U.S.A. (Utah)	153	4647	1964		
Glen Canyon	U.S.A. (Ariz.)	216	33305	1964		
Anderson	U.S.A. (Calif.)	72	110	1950		

Other possible cases
Height in meters follows dam name (n.a. = not available).
U.S.A. — Shasta (183), Calif.; San Luis (116), Calif.; Palisades (82), Utah; Clark Canyon (40), Mont.; Kerr (n.a.), Mont.; Cabin Creek (n.a.), Colo.; Rocky Reach (n.a.), Wash.
Australia — Eucumbene (116); Warragamba (137).
Pakistan — Mangla (116).
Spain — El Grado (130).
India — Kinnersani, Parambikulam, Sharavathi, Ukai, Ghirni, Mula (all n.a.).

*The relationship between the Oroville earthquake and the filling of the reservoir is not as clear as for the other major induced earthquakes. See further comment.

Source: Goldsmith & Hildyard, 1984, 114.

this is the increased incidence of stable sliding (fault creep) brought about by higher pore-water pressure in the vicinity of the reservoir. With more and larger dams being contemplated the probability that they will be sited in less favourable seismic zones will increase. Especially in developing countries the scientific basis for responsible site selection is often insufficient. This will add to the risks to be taken under the impact of strong pressures to develop.

A rapid emptying of reservoirs may lead to further disturbances due to scouring, in the dam lake as well as in the river bed downstream. Earthquakes may damage the dam especially when shoddy workmanship, and inadequate engineering standards have been applied. The latter are a matter of concern by themselves. For instance, more than one hundred catastrophic dam failures have been reported since 1930 for the USA alone (cited in Petts, 1984, 10), giving testimony to the fact that engineering advances in dam construction are not without substantial costs. Engineering shortcomings can be expected to exist in old dams where the danger of induced seismicity was not recognised, and for new dams in the face of threatening cost overruns and technically inadequate or corrupt oversight arrangements.

2.1.2 Floods

There are serious problems in many river basins through the world, particularly in the monsoon and typhoon areas of densely populated South and East Asia. With rising populations the damage of floods tends to increase over time, despite corrective action. The main methods used today for 'controlling' floods are the building of embankments to contain flood waters within rivers, and the construction of reservoirs in which flood waters can be impounded before being released at controlled rates and at a later time.

These structural controls have been repeatedly shown to be defective for two reasons. By containing a river within concrete embankments, one does not reduce the total **volume** of flood waters, but one dramatically increases the river's **rate of flow**. The flood waters are literally propelled downstream where they will cause potentially increased damage as river deltas are intensively used for agricultural production and also are near the location of large urban centres and major harbours. Channels or canals should therefore not be regarded as structural control mechanisms but as 'flood threat transfer devices'. The structural devices themselves, apart from being of dubious efficacy, are also costly, and sometimes well beyond the financial resources available to poor and heavily indebted countries.

Currently, the *Bangladesh Action Plan for Flood Control* has become a focal point in discussions about flood control on a large scale. It was formulated following the 1988 flood in which 46 percent of Bangladesh was inundated, 2,500 people died and 30 million people were temporarily displaced from their homes. Flood waters reached the diplomatic centre of the capital city Dhaka for the first time in memory. In the following year, and coordinated by the World Bank, a series of four studies were conducted to consider possible aid programmes for alleviating flood problems and increasing agricultural production. These studies were carried out by a French Engineering Consortium, the UNDP, USAID and the Government of Japan (see Bangladesh Action Plan, documents and criticisms, 1992). At the heart of the controversy lies a judgment whether the main rivers in Bangladesh are controllable rivers at all, and on this experts are divided, as is reflected in the different reports.

2.1.3 Sedimentation patterns

Dams interrupt the carrier function of rivers in transporting sediments from upstream origin to deposit them in down stream locations. By depositing such sediments before the dam, they have serious effects on the functioning of dams in the short run and may threaten the life expectancy of the man-made lakes in the long run.

The volume of suspended loads carried by rivers tends to be systematically underestimated, as is shown in Table 7 and 8.

Table 7. Annual Rates of siltation in selected reservoirs in India (in acre feet)

Reservoir	Assumed Rate	Observed Rate	Obs\Ass
Bhakra	23,000	33,475	1.46
Maithon	684	5,980	8.74
Mavurakshi	538	2,000	3.72
Nizamsagar	530	8,725	16.46
Panchet	1,982	9,533	4.81
Ramganga	1,089	4,366	4.01
Tungabhadra	9,796	41,058	4.19
Ukai	7,448	21,758	2.92

Source: Report of the Irrigation Commission, cited in The State of India's Environment, 1982. Chapter 4 Dams.

Table 8. Annual Rate of Silting (Hectare/Meters of Silt) per 100 Sq Km of Catchment Area.

Project	Year of Impounding	Assumed while dam in built	Observed Surveys was	Surveys Conducted in
Maithon	1956	1.62	13.10	1963,1965,1971
Mayurakshi	1955	3.61	16.43	1965,1970
Ramganga	1974	4.29	18.19	Sediment Inflow
Ghod	1966	3.61	15.24	Inflow-Outflow
BeasUnit2	1974	4.29	14.29	Sediment Inflow
Ukai	1971	1.47	10.95	Inflow-Outflow
Narmada	constr.	1.55	5.62	Inflow-Outflow
Tawa	1974	3.61	11.15	Sediment Inflow
Sivajisagar	1961	...	15.24	1966, 1971

Source: National Commission on Agriculture, 1976, cited in Claude Alvares and Ramesh Billorey, Damning the Narmada: The Politics Behind the Destruction, *The Ecologist,* Vol 17, No 2, 1987.

Though the data are clear by themselves, the figures do not reveal the extent to which the original planning figures incorporate estimated sedimentation load before dam construction **and** the secondary effects of developments induced by dam construction.

The effects of underestimating sediment loads and changes in sedimentation patterns on the life expectancy of reservoirs can be dramatic. Reservoir sedimentation will progressively alter the character of discharges downstream, and thereby subvert the purposes for which river impoundment was initiated. The Huang He, in China, has the highest sediment load in the world (1.6 billions tonnes per year), and of its impoundments, the Heisonghi Reservoir lost near 20 percent of its storage capacity within 3 years of completion; even after operations to reduce the sedimentation rate, the expected life of the reservoir is less than 80 years. Other large multipurpose reservoirs in the same catchment have a similar fate: the Sanmanxia, for example, lost 40 percent of its storage capacity in the first 20 years after completion. But also in developed countries major miscalculations occur: in Southern California, Big Tujunga Dam lost 70 percent of its storage capacity in less than 4 years, as a result of high sediment yields, and major floods now pass the spillweir only slightly attenuated (cited in Petts, 1984, 53).

Indeed, many reservoirs in areas with high sediment-yield have a life expectancy of less than 100 years. Consumption losses will decrease, and flood-peaks will increase as the reservoir becomes infilled with sediments. It seems inevitable that, with increasing population pressures along rivers and dam lakes, sedimentation rates will accelerate. Life expectancy of reservoirs will be further reduced and thereby the scope for expanding the productive use of water for irrigation development in water scarce areas. In some countries, such as India and Pakistan, but also in Java, Indonesia, concerns about approaching limits of affordable irrigation development are intensifying, the more so as new developments inevitably will have to take place in more difficult terrains as the number of favoured sites is limited. Consequently, major defensive investments are required for dredging and controlling developments along the lake shores and river streams to prolong, if possible, the life expectancy of dams.

Reduced river flows tend to elevate riverbeds downstream. Relevant information on China during the 1980s has recently become available (Smil, 1992). Diversions of the Huang He waters, amounting to more than a quarter of the total flow in dry years, reduces the silt transport to the Bohai Bay; up to one quarter of the high sediment load, some 400 Mt, is now deposited each year on the river bed in Henan and Shandong, aggravating the principal long term threat for the Plain's inhabitants, i.e. the **inexorable elevation of the river bed above the surrounding countryside.** In the lower reaches in Henan and towards the estuary, the river is confined between about 1400 km of dykes which are at least 3-5 meters, and up to 11-15 meters above the surrounding country side, protecting roughly 250,000 km2 of the North China plain. With higher erosion on the Loess Plateau, the river's silt load has increased at least 25 percent since the early 1950s, and the average riverbed rise has been one meter per decade.

2.1.4 Hydrological effects

Hydrological effects may be captured under two headings: water losses and the effects on the timing of discharges. Hot climates lead to high evaporation rates in dam lakes. Seepage from reservoirs, from conveyance canals and field channels and due to damaged minor structural works can be very substantial as well. In general, one then 'captures' less water for effective use than expected, and the planning of water use for secondary activities such as irrigation, may have to be scaled down from original expectations or plans. The timing of water discharges may lead to changes in agricultural seasons. Examples of the hydrological effects of river impoundment are given in Table 9 (Petts, 1984, 28-9).

The range of induced changes in flow regime can be bewildering. The Table shows cases of (i) reduced average annual runoff, (ii) reduced seasonal flow variability, (iii) altered timing of annual extremes to (iv) reduced flow magnitudes.

As the examples of Lake Nasser, or River Churchill show, the size of the changes in fresh -water availability through evaporation can be enormous, while induced salt water intrusion in the delta's may pose a serious threat to their fertility for agricultural

Table 9 Some examples of the hydrological effects of river impoundment.

River/Reservoir, Country	Reported hydrological changes	Source
	REDUCED AVERAGE ANNUAL RUNOFF	
River Nile/Lake Nasser, Egypt	Average annual water-yield reduced: losses of nearly 500 × $10^6 m^3$ yr through evaporation	Waffa & Labib (1973)
Hawkesbury–Nepean River Warragamba Dam, Australia	Average annual runoff reduced by between 19% and 28%	Warner (1981)
River Churchill, Canada	Average discharge reduced from 1000 m^3 per s to 200 m^3 per s	Dickson (1975)
River Zambezi, Mozambique	Saltwater incursion in the coastal floodplain and delta area induced by reduced freshwater discharges	Hall *et al.* (1977)
River Dnieper, Kakhovka Power-station, USSR	Average annual runoff reduced by 20%	Zalumi (1970)
	REDUCED SEASONAL FLOW VARIABILITY	
River Columbia, Dalles Dam, USA	Maximum average monthly flow reduced by 50%	Trefethen (1972)
River Yarmouk/R. Jordan, Israel	Flow will be reduced to a minimal level throughout the year	Ortal & Por (1978)
River Damodar reservoirs, India	Impoundments designed to tranform the seasonal river into a perennial one	Jain *et al.* (1973)
River Peace, Bennett Dam, Canada	Flow-range compressed from 150 to 9000 m^3 per s to 500–2000 m^3 per s	Kellerhals (1971)
River Gordon, Tasmania	Minimum regulated flows three times natural flow	King & Tyler (1982)
	ALTERED TIMING OF ANNUAL EXTREMES	
River Jordan, Israel	50 years of dam construction for power and irrigation supply purposes have transformed the flow-regime from a winter to a summer high-flow	Ortal & Por (1978)
Murray–Darling rivers, Australia	Impoundments have effectively reversed the natural pattern of runoff: the former summer low-flow period has been replaced by 'peak' flow in response to irrigation demand	Cadwallader (1978)
River Vir, Czechoslovakia	Natural flow-regime characterized by two periods of high-flow in March and July, but regulated river has only one (in May)	Peňáz *et al.* (1968).
River Columbia, Dalles Dam, USA	Month of minimum average flow is now 1 month earlier, and high-flow season has been delayed by several months	Trefethen (1972)
	REDUCED FLOOD MAGNITUDES	
TVA Scheme, USA	1957 flood at Chattanooga; flood stage reduced from 7.3 m to 0.7 m	Elliot & Engstrom (1959)
Central European Rivers	50 years' flood reduced by 20%	Lauterbach & Leder (1969)
River Colorado, Glen Canyon Dam, USA	10 years' flood reduced by 75%	Dolan *et al.* (1974)
River Nile, High Aswan Dam, Egypt	'Flood peaks' reduced by 75%	Kinawy *et al.* (1973)
River Damodar, Panchet Reservoir, India	Design flood of 28 300 m^3 per s will be reduced to 5660m^3 per s	Jain *et al.* (1973)
River Peace, Bennett Dam, Canada	Flow stabilization reduced flood stages for 1200 km below the dam	Geen (1974)
River Zambezi, Kariba Reservoir, Africa	Flood controls effective for 130 km downstream	Guy (1981)
	IMPOSITION OF UNNATURAL PULSES	
River Vyrnwy, Lake Vyrnwy, UK	Regular monthly releases of 1.16 m^3 per s for 5 days during summer (5 times normal controlled low-flows)	Severn Trent Water Authority (pers. comm.)
Upper Kennebec River, Maine, USA	Periodic instantaneous, flow-fluctuations from 7.8 m^3 per s to 170 m^3 per s	Trotzky & Gregory (1974)
Colorado River, Glen Canyon Dam, USA	Daily fluctuations of water-depth by about 1.5 m	Turner & Karpiscak (1980)
Zambezi River, Kariba Reservoir, Africa	Sudden release increased flow from 700 m^3 per s to 4531 m^3 per s	Begg (1973)
Zambezi River, Cabora Bassa Dam, Mozambique	Flow cut from 3000 m^3 per s to 60 m^3 per s during four months of filling: recommended minimum discharge of 400–500 m^3 per s ignored	Davies (1975)

Source: Petts, 1984, 28–29

production. Where delta's are also heavily populated drinking water supplies will be negatively affected as well. Progressive dam construction on the River Jordan has transformed the flow regime from a winter to a summer high-flow. While there are several cases where floods are now being effectively controlled for various distances on the river, in other cases unnatural impulses are added to the river, and these may often be related to conflicts in dam operations (see 2.2).

2.1.5 Ecological effects

Impoundments give rise to dramatic changes in the characteristics of rivers. Biological effects for **flora** and **fauna** occur through effects on water quality, changes in geomorphology (water depth, flow velocity, water temperature) on vegetation and on the growth of organisms such as plankton and other feedstock for fish population. Dams also impede access to migrating fish species. In general, dam building will lead to **loss of bio-diversity**. These effects of impoundments upon the downstream river may be viewed in terms of three orders of impact: **(i)** A first order impact occurs simultaneously with dam closure, and effects the transfer of energy and material into and within the downstream river. **(ii)** Second-order impacts are the changes in channel structure and primary production, resulting from first-order impacts. These impacts may require a time-period of between 1 and 100 years, or more to achieve a new 'equilibrium' state. **(iii)** Third-order impacts will reflect all the changes of first- and second-order, and the fish population will also be influenced by changes in the invertebrate community, which provides the major food-supply for many species. Interaction effects between second and third order effects may be substantial and can spread over long time spans.

According to Goldsmith & Hildyard (1984, 92-102), the loss of fish in terms of fish yield throughout the river basin can, in most cases equal - or even exceed - temporary gains made in a dam's reservoir for the following reasons:

(i) Dams tend to reduce the catch of migratory fish species by preventing them from reaching their spawning grounds. The higher the dams the more fish will be lost, or delays in climbing artificial 'ladders' to swim over the dam, may prove to be fatal.

(ii) The creation of large storage reservoirs reduces the flow of rivers. This results in a fall in water levels of those lakes and inland seas which are fed by rivers, thereby destroying fish habitats.

(iii) Building storage schemes has led to an increase in the salinity of many rivers. In part this is due to: highly saline drainage waters from irrigated land, and in part, due to reduced flow of the rivers themselves to dissolve the salts, or at least to reduce harmful effects of salinity build-up.

(iv) The silt previously deposited down stream and in river deltas is now trapped and not used. Often this silt is very fertile and was historically used to replenish soil nutrients lost in agricultural production downstream, such as in the Nile valley in Egypt. Currently, fertilizers have to be supplied to the land to compensate these nutrient losses.

(v) Aquatic weeds in standing waters cause several problems. The proliferation of weeds affects fish populations in a number of ways. First, they increase water losses through evapo-transpiration, thus reducing water levels in the reservoirs. Second, by virtue of their sheer mass they reduce reservoir capacity and thereby restrict the habitat of fish. Third, when these weeds rot they use up valuable oxygen which may result in high fish mortality. Fourth, by diminishing the sunlight both at the surface and in the waters below, weeds reduce the biological productivity of the reservoir which in turn reduces the number of micro-organisms. In some deep reservoirs methane may be formed which poisons the water.

In addition to effects on aquatic life, weeds such as *salvina*, frequently forms broad 'mats' which anchor among submerged trees and shrubs. This restricts the movements of (fishing and other) boats, but also blocks hydro-electric turbines and even harbours. Although those problems can largely be avoided by clearing forested areas before flooding, such clearance is rarely undertaken (Goldsmith & Hildyard, 1984, 97). If it is done the effects on the soil and on sediment transport may dramatically increase to accelerate the rate of reservoirs silting up. Aquatic weeds also can have serious effects in irrigation systems, causing blockages of irrigation canals and thus reductions in the reach of the irrigation canals when the latter are poorly maintained. Herbicides used to temporarily - due to fast regrowth - eliminate aquatic weeds also kills species of aquatic life, while allowing others to proliferate, leading to further disruptions in the eco-system. Pesticide pollution from drainage of agricultural lands has similar effects on fish populations.

Rivers not only function to transport sweet water and thereby support habitats. They are also used as 'sewers', to transport pollutants, and this leads to a sharp deterioration of the **quality** of river water. Pollution of rivers stems from several sources. Mining operations often lead to water poisoning. In fact, several of the case studies brought before the *International Water Tribunal* (Amsterdam, February 1992), involved water poisoning from gold mines and copper mines. 'Modern' agriculture, with its use of pesticides and weedicides, drains residuals back into river streams. Industrial development often produces many harmful joint-products which are discharged into rivers without water treatment and purification. Similarly, human settlement wastes often find their way directly into river stream flows untreated.

Information collected by the World Bank for the *World Development Report 1992* indicates that in high-income countries water quality in rivers is far better than in low-income countries and that the quality of river water is deteriorating in low income countries to unacceptable levels. (Figure 3). While higher levels of development also afford high-income countries to devote resources to maintain or even improve water quality, low income countries often do not have the necessary means to do both.

The effect of building dams in rivers is that pollutants are no longer being transported towards the sea where at least many of them will be degraded or where concentrations are diluted to reduce the danger of ecological or human risks. Instead, these pollutants accumulate in man-made 'sinks' in the dam lakes where they may rather quickly build up pollution to dangerous levels. Cess pools are thus 'internalised' within countries rather than pushed out into the sea. When heavily contaminated river flows are subsequently fed into irrigation channels for agriculture and, as is often the case, for drinking water, these dangers spread more widely.

Within Western Europe, the continental countries take the problem of water quality and the need for proper water treatment before discharge more serious than in the U.K. where the prevailing attitude seems to be that water treatment expenditures can be avoided by disposing polluted waters into the sea through the use of rivers as sewers. Such a strategy involves risk-taking in the regenerative capacity of the sea to degrade pollutants, compared to a risk-avoidance strategy of serious environmental hazards through discharging pollutants in uncontrolled quantities.

2.2 Dam operations and conflicting objectives

With new dams becoming larger and increasingly having multipurpose objectives, and with older dams being modernized towards meeting similar objectives, it should be realised that conflicts among objectives are being built into the actual operations of the dams.

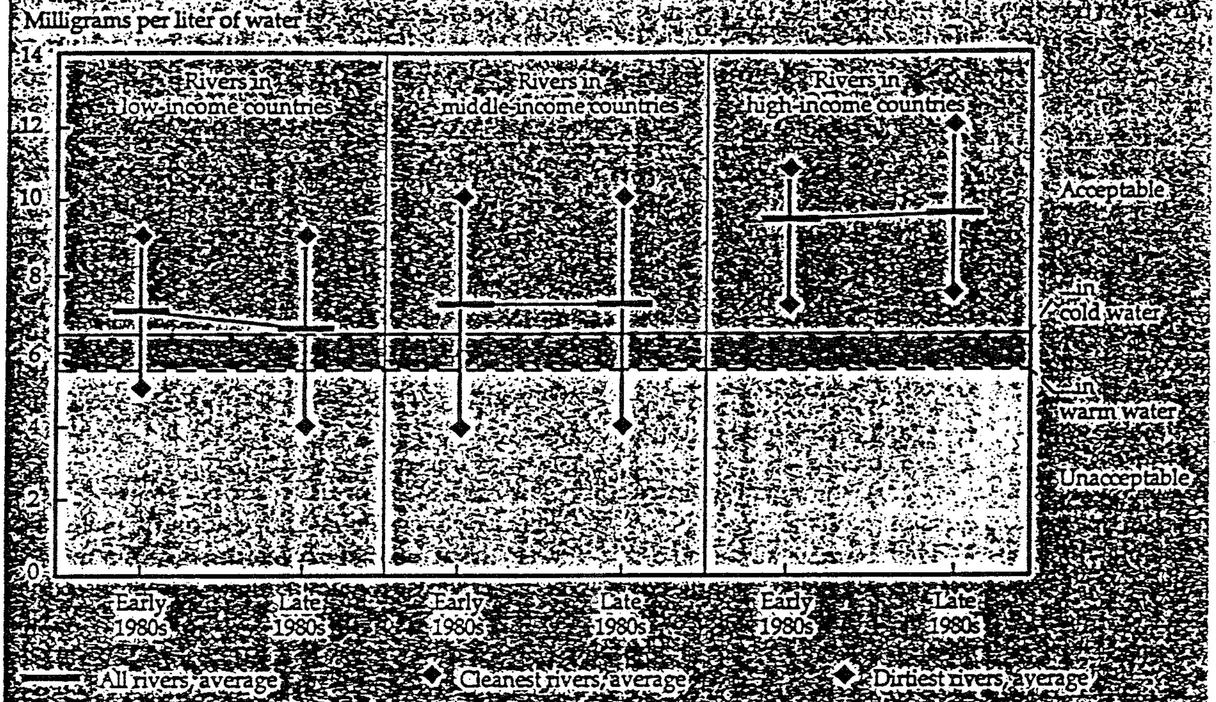
To illustrate some of the issues, major dam types and attending control mechanisms are shown in Figure 4. From an operational point of view, small upstream reservoirs and large downstream impoundments cannot be substituted for one another in basin-wide flood-control schemes, because they provide protection for different parts of a valley. To be effective for combined purposes, a reservoir must have a large capacity.

For most supply purposes (hydro-electric power, navigation and irrigation etc.), the **conservation-storage** should be maintained as **fully** as possible in order to have sufficient reserve to maintain supply during periods of droughts. In many areas of Africa and Asia the risk of drought is sometimes one in two or one in three years, implying that periods for reservoir recharge may be rather short.

Figure 3. Dissolved oxygen in rivers: levels and trends across country income groups

No improvement for aquatic life in dirtiest rivers in low- and middle-income countries

Figure 2.1 Dissolved oxygen in rivers: levels and trends across country income groups



Note: Data are for twenty sites in low-income countries, thirty-one sites in middle-income countries, and seventeen sites in high-income countries. "Cleanest rivers" and "dirtiest rivers" are the first and last quartiles of sites when ranked by water quality. Periods of time series differ somewhat by site. U.S. Environmental Protection Agency water standards for supporting aquatic life are used as the criteria for acceptability.
Source: Environmental data appendix table A.4.

Source: World Bank, World Development Report 1992, 46.

Figure 4. Major dam types

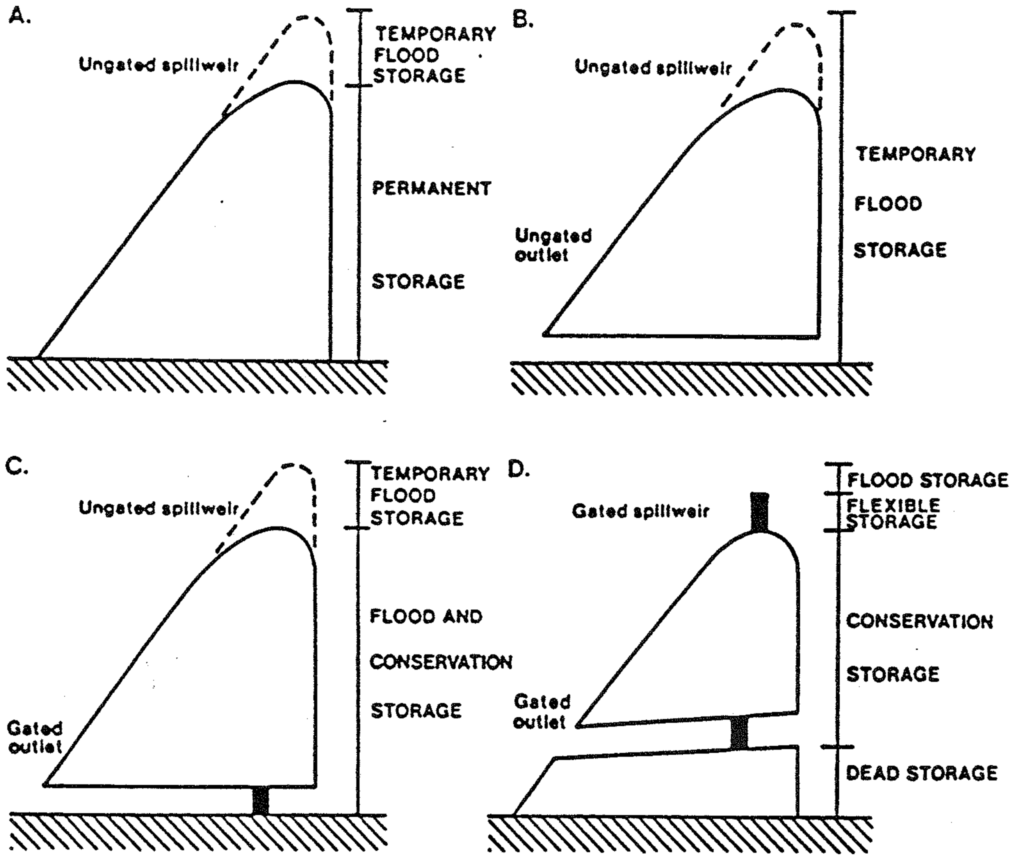


Fig.4 . Major dam types: a simple conservation dam (A), flood-detention dam (B), and structures for multipurpose operation (C and D).

Source: Petts, 1984, 30.

The provision of **flood-control storage**, on the other hand, requires that a storage volume is reserved solely for the absorption of flood discharge. The water volume retained within the flood-control storage should therefore be kept as **low** as possible, so that unexpected high runoffs can be contained. Many reservoirs are also allocated a 'dead' storage volume, below the lowest outlet level and unavailable to supply use. It may become the 'sink' for sedimentation and pollutants.

Supply needs may conflict with each other, and a classic conflict is the choice which often needs to be made between discharges for irrigation as compared to discharges for electric power. The water needs for power generation normally do not coincide in time with those for irrigation. Where most hydro-electric power stations serve the needs of urban and industrial development, the choice to be made in dam operations presents itself as an **urban - rural** conflict. But the situation is often more complex. Where part of the electricity is used in fertilizer factories or in agro-processing industries, or to fuel electric motor pumps of tubewells pumping ground water for irrigation, the issue is framed in terms of supplying **public** water from dams and irrigation channels or public deep tubewells, or supplying augmented **private** water from mostly privately owned tubewells.

Where the needs for electric power are continuous and growing at rapid rates, fluctuations in water levels due to 'buffering' inflows and water discharges at the dam are disruptive. Hence, water inlets for power generation should be from 'under shot' rather than 'overflow' sources (Fig. 4: C-D). However, undershot inlets are more threatened by the build-up of sedimentation before the dam. Continuous dredging may well be needed to keep the power station inlets free.

Dams with gated outlets will have a variable impact upon the flow regime of the downstream river, depending upon their individual operating schedules. Three main operating procedures may be distinguished (Petts, 1984, 31):

(i) **The Insurance Method** is concerned with the maintenance of minimum flows. Based upon knowledge of the driest probable year, only enough water is released to maintain a predetermined minimum flow at the point of regulation. All other conservation-storage is held in reserve for the next dry period.

(ii) **The Annual Use Method** aims to use practically all available storage-water each year, without special regard for maintaining a downstream minimum or regulated flow. During dry years the reservoir may be emptied, allowing extreme low-flows to occur within the river downstream, although floods may be effectively controlled.

(iii) **The Hydro-power Method** combines the key features of (i) and (ii) to provide a dependable minimum flow and, at the same time, to use the total volume of stored water to the best advantage. However, the resulting short-term release-schedules must be considered in relation to the habitat structure of the channel and flood plain downstream.

Depending upon the regulatory regime man-made impulses in river flows can be induced, with sometimes quite negative consequences. Some examples are given in Table 10.

The important point to make here is that conflicts among dam operations' objectives may, and often do imply that water from headworks available for agriculture is somewhat unpredictable, regardless of variations within years and between years in rainfall and attendant stream flow. Important questions then arise whether and how buffer mechanisms can be built into the design of the irrigation network to enable flow regulation in accordance with agricultural needs, and in different parts of the command areas. Derived from this is the clear need for all system operators to be timely informed about water availability and that this information is also effectively communicated to water users. There is wide agreement that such information is rarely available and lack of communication between different levels of system operators is the rule in Asia as well as Africa. Communication equipment is not available or out of use.

Immediately below a dam, the impact and suction generated by water flowing over a spillweir into the channel can produce a considerable scour-force. Rates of channel-bed erosion below dams are typically greater than erosion rates within natural rivers at least for several years after dam closure. The erosional processes tend to dominate from year to year, whereas in natural rivers alternating erosional and depositional processes maintain the channel in quasi-equilibrium. Degradation of the river bed can affect a considerable length of river. Examples are given in Table 11.

Secondary effects of river channel deterioration on downstream regulatory structures should be noted as well. For instance, new hydro-electric works linked to the Mtera Dam were completed in the Great Ruhaha River in Tanzania in 1982[3]. Induced and unanticipated scouring of the river bed quickly undermined and, in 1991, led to the near collapse of a major diversion weir, some 20 km downstream from the dam. This weir supplies the two Kilombero sugar plantations with water and the sugar factories with electricity, and accounting for over 40 percent of national sugar production[4].

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3 Within a decade the electricity supply from the hydro power project is facing already considerable problems because of excessive sedimentation-yields threatening the power station inlets. No provision was made, in this Nordic countries financed project, to facilitate continuous dredging which is clearly required.

4 Personal communication, January 1992, during mission to evaluate Netherlands support to the sugar sector in Tanzania.

Table 10. Examples of pulse-releases to regulated rivers.

Reservoir, River	Pulse and Cause	Source
Fort Randall Dam, Missouri River, USA	Daily fluctuations, from nearly zero to over 1000 m^3 per s in summer, and 500 m^3 per s in winter, due to navigation and power-peaking demand.	Livesey (1963)
Lake Kariba, Zambezi River, central Africa	Sudden changes of water-level in response to demand for electricity and flood-regulation: by opening one gated outlet the downstream flow can be increased from about 700 m^3 per s to 2000 m^3 per s in 30 minutes, producing a stage rise of 5 m below the dam.	Begg (1973)
Canyon Dam, Guadalupe River, USA	A constant flow of 4.5 m^3 per s from early January through March increased suddenly to about 20 m^3 per s in mid-April.	Hannan *et al.* (1979)
Glen Canyon Dam, Colorado River, USA	Vertical, daily stage fluctuations up to 4.5 m in response to power demand.	Dolan *et al.* (1974)
Tallowa Dam, Shoalhaven River, Australia	Normal constant flow of 45 m^3 per s terminated: outlet valve closed over a period of 15 minutes and within 30 minutes the channel bed was dry, except for four deep pools, for 200 m below the dam.	K. A. Bishop & Bell (1978)
Jackson Lake, Snake River, USA	Releases for irrigation supply cause violent fluctuations of discharge: flow reductions from 2.8 to 0.3 m^3 per s in less than 5 minutes, caused a drop in river stage by 0.3 m.	Kroger (1973)
Flaming Gorge Dam, Green River, USA	Discharge fluctuations from 10 to 70 m^3 per s increased water depth of 65 cm 11.7 km below the dam, but this was attenuated to only 10 cm about 100 km further downstream.	Pearson *et al.* (1968)
Kakhovka Power Station, River Dnieper, USSR	Tailwater flow fluctuations by 1.5 m daily, due to changing power demand.	Zalumi (1970)

Source: Petts, 1984, 52

Table 11. Observations on channel degradation below dams.

Source	River/Location	Degradation: Length of river affected (km)	Degradation: Rate (mm per yr)	Degradation: Volume ($10^6 m^3$)
Hathaway (1948)	S. Canadian River, Conchas Dam, USA.	32.2	-	26.9
Komura & Simons (1967)	Colorado River, USA Hoover Dam Fort Peck Dam	145 39	217.7 110.8	- -
Pemberton (1975)	Colorado River, USA, small coffer-dam	9.7	-	2.17
Lawson (1925)	Rio Grande, Elephant Butte, USA	150		
Stanley (1951)	Colorado River, USA Parker Dam Imperial Dam	237	- <508	3.8 1.8
Livesey (1963)	Missouri River, USA, Fort Randall		304.8 for first 2 yrs then 30 for the next 8 yrs	
Patrick *et al.* (1982)	Missouri River, USA, Garrison Dam	64		
Leopold *et al.* (1964)	Red River, USA, Denison Dam	160	-	3.65
Leopold *et al.* (1964)	S. Canadian River, USA, Conchas Dam	-	10	-
Leopold *et al.* (1964)	Average rate during 10 to 15 years after dam closure in USA	-	30	-
Shulits (1934)	River Saalach, Reichenhall Reservoir, Bavaria	-	152.4	-
Kinawy *et al.* (1973)	River Nile, Nag Hammadi Barrage, Egypt		Bed lowered by 0.7 m after a few years of operation	
Warner (1981)	Hawkesbury–Nepean River, Australia	36	Area of long profile, increased by 16 000 m²	
Szupryczyński (1976)	River Vistula, Wloclawek Dam, Poland	9	-	4.195
Petts (1978)	UK River Hodder, Stocks Reservoir	0.2	Channel cross-sectional area doubled	
	Camps Water, Camps Reservoir	0.15	ditto	
	River Rede, Catcleugh Reservoir	0.15	ditto	

Source: Petts, 1984, 121.

It is estimated that by 1900 the **area under irrigation** in the world was some 40 million hectares, five times that a century earlier. By 1950 the area had extended to about 100 million hectares and in 1986, the most recent year for which figures are generally available it is estimated that the **gross** area under irrigation amounted to 253 million hectares. Almost two-thirds of this area, 162 million hectares, is located in just five countries: India (56 million), China (46 million), USA (23 million), CIS, formerly USSR (21 million) and Pakistan (16 million).(Field, 1990). Information on the relative irrigation status of different country groupings is provided in Table 12 (World Bank, 1992)

Some 46 percent of Africa is too dry, with less than 75 days' rain in the year - not even long enough for even millet to mature. Another 8 percent, with 75-120 days' rain each year suffers from too variable rainfall. In the African continent as a whole some 9 million hectares were irrigated in 1985, about 5 percent of the cultivated area. This compares with 8.5 percent in Latin America and no less than 29 percent in Asia. But almost half

Table 12. Irrigation indicators.

	Irrigation	
Country Group	Share of agric land (1989).	Growth rate 1965-89 (%)
Low-income	**8.9**	**1.7**
China and India	14.8	1.7
Other Low-Income	4.8	1.8
Middle-income	**2.9**	**2.3**
Lower M-I	3.2	2.3
Upper M-I	2.6	2.3
Low- and Middle Inc.	**5.8**	**1.9**
Sub-Saharan Africa	0.6	2.2
East Asia & Pacific	9.9	1.6
South Asia	27.5	2.1
Europe	8.4	3.1
M.East & North Africa	5.5	0.8
Lat. Am.& Caribbean	2.0	2.5
Other economies	3.8	3.8
High-Income	**3.0**	**1.1**
OECD members	3.0	1.1
Other	3.0	1.1
World	**4.9**	**1.9**

Source: World Development Report 1992, World Bank.

of all the irrigated area is concentrated in the five countries of North Africa. Of the 4.8 million hectares in Black Africa, well over half is in just two countries : Sudan and Madagascar (Harrison, 1987, 153-4; FAO, 1986). The relative importance of modern and traditional irrigation in Africa is depicted in Fig. 5 (Adams, 1992, 75).

It may be noted, however, that the rate of increase in **net** irrigated area in **Asia** has been declining since the late 1960s. In the Near East there has even been an absolute decline in net irrigated areas (Table 13). Also international lending for irrigation development seems to have been declining since the 1970s as is shown in Table 14. No information is available on the question whether the countries themselves have been financing a rising or declining share of total irrigation investments.

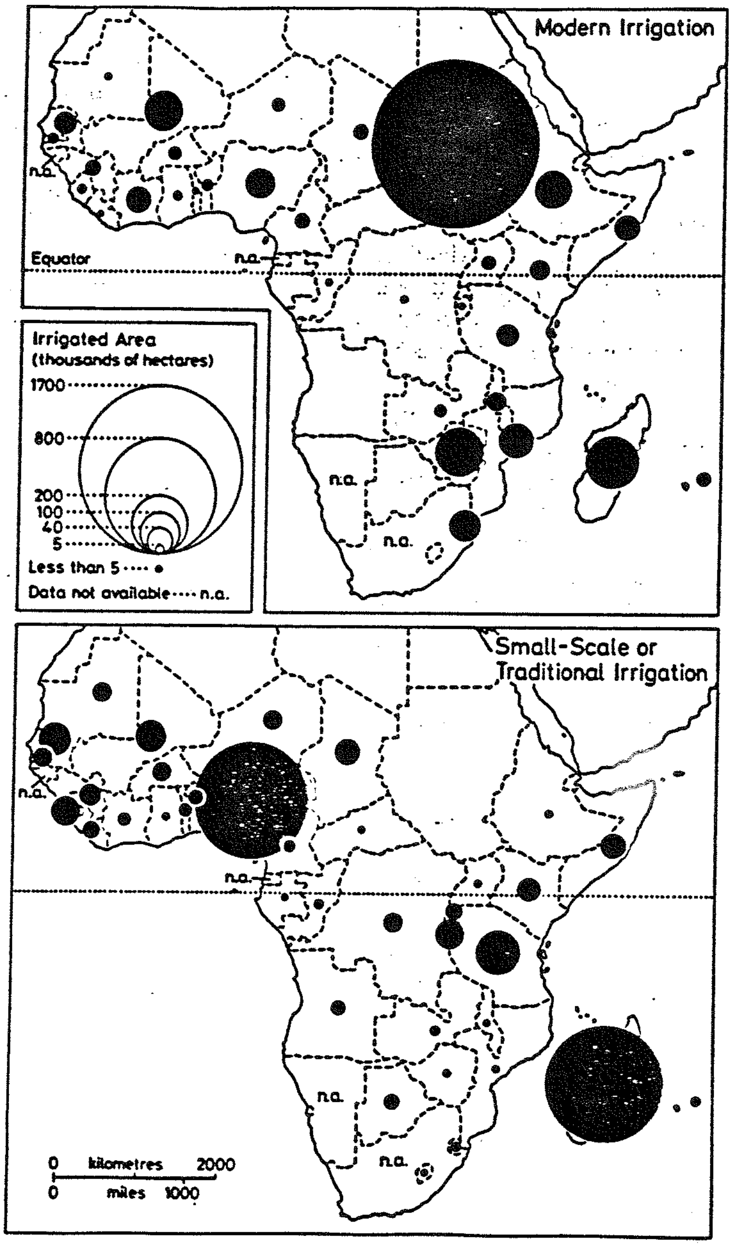
Table 13. Compound growth rates of net irrigated area in Asia (in %).

Period	SE Asia	S.Asia	China	Korea	Near East
1965-69	0.9	2.7	2.9	7.3	1.7
1970-74	4.0	1.9	2.9	3.1	0.4
1975-79	3.0	2.2	0	6.2	0.7
1980-84	2.1	1.0	0	0.8	-0.8
1965-84	**2.5**	**2.1**	**1.2**	**2.5**	**-0.3**

Source : Levine, G, R. Barker, M. Rosegrant, M. Svendsen (1988), Irrigation in Asia and the Near East in the 1990's: Problems and Prospects, ISPAN-USAID, cited in: Bhuiyan, S.I. (1989), Irrigation and Water Management for Diversified Cropping in Rice Irrigation Systems: Major Issues and Concerns, ODI/IIMI Irrigation Management Network Paper 89/1e, June.

Figure 5.

Irrigated Areas in Sub-Saharan Africa, 1982



Source :FAO Investment Centre (1985) ***Irrigation in Africa South of the Sahara***, FAO, Rome.

Figure 4.1 Area of modern and traditional small-scale irrigation in Africa

Source: Adams, 1992, 75.

Table 14. Average annual lending and assistance for irrigation in South and South East Asia by four major lending agencies, constant 1980 prices (million $).

	South-East Asia					South Asia				
Period	WB	ADB	USAID	OECF	TOTAL	WB	ADB	USAID	OECF	TOTAL
1969-70	-	35	-	6		-	18	-	0	
1971-73	-	61	-	7		-	8	-	0	
1974-76	319	52	-	16		349	32	-	0	
1977-79	467	134	-	29		514	85	-	4	
1980-82	237	153	17	31	438	651	100	54	15	820
1983-85	147	87	5	59	298	533	74	68	10	685
1986-87	88	96	9	18	211	317	48	29	3	397

Source: Levine, G, R. Barker, M. Rosegrant, M. Svendsen (1988), Irrigation in Asia and the Near East in the 1990's: Problems and Prospects, ISPAN-USAID, cited in: Bhuiyan, S.I. (1989), Irrigation and Water Management for Diversified Cropping in Rice Irrigation Systems: Major Issues and Concerns, ODI/IIMI Irrigation Management Network Paper 89/1e, June.

As a result of high costs and the experience of failure, progress in **African** irrigation has slowed radically. Between 1968 and 1974-76, the irrigated area expanded by 4 percent a year. Since then, the annual rate of growth has fallen by more than half, to 1.7 percent a year. Meanwhile, older irrigation systems have deteriorated through lack of maintenance. Most major donors are now extremely cautious about investing in ambitious new irrigation projects in Africa. By 1985, the World Bank had virtually stopped lending for new large-scale projects (Harrison, 1987, 157).

As a counterpoint to this picture of rapid irrigation expansion during the 1950s and 1960s, and continuing though at declining rates since the 1970s, it was reported at the 1987 Congress of the International Commission on Irrigation and Drainage, that more than half the irrigated area in the world today is in need of rehabilitation or modernisation (Field, 1990). FAO estimates that 50 percent of the world's irrigated land is salinized to the extent of effecting productivity (cited in Carruthers, 1986). Others put the figure even higher. Thus, Victor Kovda argues that, worldwide, salinization affects 60 to 80 percent of irrigated land - between 1 and 1.5 million hectares have to be abandoned for agriculture each year. Other studies put the figure for de-commissioned agricultural land lower, though still at several hundred thousands hectares each year, leading to major agricultural losses and major displacements of agriculture- dependent populations (Goldsmith & Hildyard, 1984, 139ff). According to Harrison (1987, 157), the expansion of irrigation in Africa has probably now reached a standstill, where new land coming under irrigation barely balances the losses of irrigated lands through deterioration.

In terms of **agricultural production** the 17 percent of the total irrigated area cropped world-wide contributes more than one third of the world's food production. In the developing world, almost 60 percent of the production of major cereals, rice and wheat, derives from irrigation. The major agronomic advances in successful crop breeding, the High-Yielding Varieties (HYVs), are characterised by high response to external inputs such as fertilizer, but are conditional upon adequate water and water management regimes. Hence, irrigation development and the HYVs have spearheaded agricultural intensification strategies. In addition, area expansion but with low yields has contributed in the past to expanding agricultural production. But in many countries the land frontiers are gradually closing.

Irrigation development, often in conjunction with hydro-power development is expensive, yet it has attracted vast financial resources, also from bilateral donors and the international development banks. Unit cost of new irrigation development are rising, and investments in irrigation have been repeatedly criticised. Early mostly negative, and rather general evaluations of donor irrigation investments are contained in Widstrand (1978) for UNEP, Carrruthers (1983) for the OECD countries, Steinberg et.al.(1983) for USAID, Van Steekelenburg and Zijlstra (1985) for the EDF. More recently studies have appeared concerning irrigation in Africa, which repeat many of the earlier criticisms: Moris and Thom (1990) for USAID, Aviron Violet et.al.(1991) for OECD/Club du Sahel, Barghouti and LeMoigne of the World Bank (1990). In South and East Asia irrigation is woven into all agricultural development discussions. In India, for instance, considerable work is undertaken in the context of the Narmada Valley Development and National Water Management Project programmes.

Irrigation in the developing world is almost entirely by surface methods, based on river diversion structures and attending canal systems. In view of the contradictory trends in irrigation development in recent decades, Chambers states that:

> *'Canal irrigation management must now present some of the greatest practical and intellectual challenges facing humankind'* (Chambers, 1988, xiii).

3.1 Problems of irrigation

3.1.1 Salinization and waterlogging

Permanent irrigation affects the water and salt balance in the eco-system. 'Weathering' - the natural, chemical, biological and physical processes which lead to the gradual breakdown of rocks and other geological formation - leads to the release of natural salts, which are generally to be dissolved in rain water. That water percolates into the underlying ground water or is washed away in streams and rivers. Adding water from rivers to the land for irrigation increases surface levels salts due to evapo-transpiration. These salts may, in part, percolate into the ground water. When drainage is poor, standing water enables more evaporation leaving more surface salts, while the soils themselves become waterlogged. Consequently, the ground water table rises. Where the salt content of ground water is rising, surface and ground water need to be kept separated which is becoming progressively more difficult under perennial irrigation.

The information available for the area of land provided with drainage is considerably less comprehensive than the information on irrigated areas, and does not allow estimation of the area of drainage directly associated with irrigation. The total area of land protected by drainage and flood control is estimated to amount to about 170 million hectares. In contrast to the area of land under irrigation, the greater part, about two-thirds, is in the developed countries with only one-third in the developing countries (Field, 1990).

Salinity has major negative effects on agricultural production and yield levels. Advanced salinization necessitates the abandoning of the lands affected for agricultural production. Examples on the degree of salinization in various large schemes in India, is given in Tables 15 and 16.

Table 15. Extent of waterlogging and soil salinity in selected irrigation projects in India. (thousand hectares)

Irrigation project	State	Extent of Waterlogging	Salinity
Sriramsagar	Andra Pradesh	60 (48)	1 (1)
Tungabhadra	AP / Karnataka	5 (1)	24 (7)
Gandak	Bihar / UP	211 (21)	400 (40)
Ukai-Kakrapar	Gujarat	16 (4)	8 (2)
Mahi-Kadana	Gujarat/Rajasthan	82*(17)	36 (7)
Malaprabha	Karnataka	1*(1)	- -
Chambal	MP / Rajasthan	99 (20)	40 (8)
Tawa	Madhya Pradesh	- -	7 (4)
Rajastan Canal	Rajasthan	43 (8)	29 (5)
Sarda Sahayak	Uttar Pradesh	303*(28)	50 (5)
Ramganga	Uttar Pradesh	195 (33)	353 (60)
	Total	1015	948

* Figures include water logging and soil salinity
Figures in parentheses are the percentages of the irrigation potential created in the respective command areas.

Source: Joshi, P.K. and A.K. Agnihotri, An assesment of the adverse effects of canal irrigation in India, IJAE 1984 Vol 39.3.

Table 16. Annual increase in waterlogging and soil salinity in selected irrigation projects (thousand hectares)

Irrigation project		Waterlogging	Salinity
Sriramsagar	Andra Pradesh	10.0	0.2
Tungabhadra	AP / Karnataka	0.2	1.9
Gandak	Bihar / UP	3.5	36.4
Ukai-Kakrapar	Gujarat	0.6	0.3
Mahi-Kadana	Gujarat/Rajasthan	3.9*	1.7
Malaprabha	Karnataka	0.5*	-
Chambal	MP / Rajasthan	7.6	3.1
Tawa	Madhya Pradesh	-	1.1
Rajastan Canal	Rajasthan	3.9	2.7
Sarda Sahayak	Uttar Pradesh	5.7*	0.9
Ramganga	Uttar Pradesh	27.9	50.4

* Figures include water logging and soil salinity

Source: Joshi, P.K. and A.K. Agnihotri, An assesment of the adverse effects of canal irrigation in India, IJAE 1984 Vol 39.3.

It may be noted that in some schemes average yields after a number of years of irrigation may have reverted to pre-irrigation yield levels due, at least in part, to salinization, negating the very intent of irrigation development as a strategy. In Iran, Iraq, Egypt and Pakistan more than 70 percent of the farmland is so affected. In India, a much quoted figure is 6 million ha affected by salinity (Carruthers, 1986, 266). Information on yield effects associated with salinization is given in Tables 17 and 18.

Table 17. The Impact of waterlogging on crop yields, Shaanxi Province, China.

Ground-water depth. (meters)	Harvest as a portion of normal yield Wheat (percentage)	Cotton
2 - 3	100	100
1 - 2	50	65
0.5 - 1	20	50
0.5 and higher	0	10-20

Source: Bruce Stokes, *Bread and Water: Growing Tomorrow's Food*, Worldwatch Institute, Washington DC., cited in *Water Resources Development in Asia and the Pacific. Some Issues and Concerns*, UN ESCAP, Water Resources Series No 62, Bangkok 1987.

Table 18. Average Yield of Rice covered under selected irrigation projects (kg/ha)

Irrigation project	Year of first irrigation	Period I	II	III
Sriramsagar	1974	1280	1758	2116
Gandak	1969	567	883	810
Kosi	1961	598	791	796
Malaprabha	1978	1094	1197	1279
Chambal	1967	408	467	333
Tawa	1974	912	879	671

Note: Three-Year average yield of rice
I Before irrigation
II Immediately after irrigation
III Yield 1978-81

Source: Joshi, P.K. and A.K. Agnihotri, An assesment of the adverse effects of canal irrigation in India, IJAE 1984 Vol 39.3.

Historically, the need for drainage in South Asia has not been recognised when many of the large flow-of-the-river schemes were first constructed from the last quarter of the 19th century and the early part of the 20th century. This neglect is part of the learning costs of colonial army engineers. The building up of salts is a slow and creeping process.

Possibly negative yield effects are not immediately obvious, certainly not when crop security and crop yields are compared with the pre-irrigation era.

Later on the possibility of future increases in salinity were recognised but not acted upon, often for reasons of the associated costs or of political expediency, or because the task appears too daunting to even give it a try. New irrigation projects are far more glamorous than patching up deteriorating older systems. For instance, Carruthers complains that 'the aid lobby, such as those responsible for the **Brandt Report (1980)**, specifically mention large-scale irrigation basins as a major area for agricultural investment and production expansion. But in most irrigation areas, drainage, reclamation and water control projects are needed now' (Carruthers, 1986, 266).

In connection with the High Dam at Aswan in Egypt it was argued - wrongly it now appears - that there was no need for separate drainage on the ground that cessation of the annual flood phenomenon due to the storage by the High Dam would lead to a fall in water levels downstream and this would improve the natural flow of drainage water back to the river bed (Goldsmith & Hildyard, 1984, 148).

Johnson (1988) reviews the irrigation experience of Pakistan and argues that massive investments in drainage is now inevitable if the Indus Plains are to sustain at targeted living standards the 130 million who will inhabit the region in the year 2000. He concludes that no alternative is available and, most depressing of all, that most of the costs must be borne by the users of irrigation. This is daunting because the Pakistan Government has not managed to make even the rich, among what are mostly low-income farmers, pay more than 50 percent of the recurrent cost of irrigation supplies. Normally, the capital costs of new investments are financed in part by foreign donors or by recipient governments but rarely ever by the beneficiaries directly.

Potential solutions to salinity and water logging exist but they are expensive. Horizontal drainage is complex. In areas already irrigated, the relative loss of land to build drains among fragmented and often small farm holdings are considerable, and disruptions to existing farming structures, roads and canals inspire obviously strong local opposition. Maintenance of drains is also costly and requires careful management. Lining irrigation canals will reduce seepage, but favourable effects will only last if maintenance levels of canals remain high. In cases where irrigation systems have been extended widely, there simply is not enough water available to 'flush out' surface salts by temporary increases in water supply. In addition, successful flushing upstream tends to increase salinity problems downstream, as the salts are redeposited elsewhere. In Pakistan, this phenomenon has become manifest in the lower reaches of the Indus, in Sind Province.

Moreover, primary water courses and the newly to be associated drains are often the responsibility of water-users, and one is at the interface where normally the authority and responsibility of Irrigation Departments stop and where those of field users begin. It is thus often the frontier area between public sector bureaucrats and private farming interests. Powerful land and 'water' lords may dominate the local social structure, and people may 'get killed over water conflicts'[5]. In more egalitarian social structures farmers may be too poor to be able to sacrifice part of their land for constructing drains and to pay for such investments. The more so if many people have too small land holdings and require multiple jobs to survive at all. To initiate extensive and effective drainage operations in such rural settings requires effective and mutually understanding interaction between irrigation bureaucrats from Irrigation Departments and representative organisations of land users affected by such measures. Clearly, in many countries this type of interrelations does not exist and can hardly be expected to be formed without a fundamental reorientation of irrigation and drainage bureaucracies and social organisation of affected users.

Vertical drainage, through digging deep tubewells and pumping out groundwater, is a temporary solution as the salts do not disappear from the system. It is, however, an option often favoured by public agencies (such as in Pakistan), because these tasks can be 'internalised' within existing irrigation bureaucracies, without the obvious need to interact effectively with water users as in most horizontal drainage efforts. Where groundwater itself is already saline, pumping it up to either supplement inadequate surface water or to improve natural drainage will lead to increased salt concentrations at the surface.

3.1.2 Conjunctive use of water resources

Conjunctive use of water resources relates to issues arising from the potential and actual combination of different sources of water in agricultural production. The three water sources are rainfall, irrigation water from canals or from tanks (as in South India), and ground water. Better planning of conjunctive use of water resources is needed because of water shortages in major irrigation areas for food production and growing populations, more diversified development and hopefully rising incomes. The scope for conjunctive use has increased in recent decades as a result of technological change: tubewells and motor pumps, and rising levels of the groundwater table in many areas have made groundwater accessible for large numbers of individual farmers.

But the relative weight to be given to each of these sources has very important implications for the manner in which the sub-systems of surface water and ground water are or can be managed, separately or conjunctively. What then are some of the major emerging issues arising from these trends?

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5 Interview in 1985 with WAPDA, Lahore, with the Director General in charge of IFAD supported on-farm water management improvement project.

Surface Irrigation and rainfall

Surface water (from canals) is always complementary to rainfall, except where there is no rainfall at all. But serious management problems of irrigation systems arise where rainfall patterns are such as to make rainfed agriculture potentially viable. The major issues may be clarified with help of a recent study of comparative irrigation performance in four large irrigation systems in the Indo-Gangetic plain in India: Bhakra in Haryana, Sarda in Central Uttar Pradesh, Sone in South West Bihar and Gandak in North Bihar, from West to East (Berkoff, 1990).

The Indo-Gangetic alluvial plain stretches across North India from Pakistan to Bangladesh. It supports about 40 percent of India's population and perhaps 50 percent of the irrigated area. In the West it includes one of the most successful and productive agricultural regions in India, in the East one of the least productive. Between, there is a gradual transition in physical and socio-economic conditions with rainfall, kharif cloud cover, surface flooding, rural population densities and subsistence farming generally increasing, and agricultural yields generally decreasing from West to East.

Two approaches to irrigation design and management in the region reflect these conditions. Schemes under the *North India Act* (o.a. Haryana and Uttar Pradesh) are typified by a low water duty per hectare (sufficient for 20-30% of Cultural Command Area, CCA, in kharif, and 35-45% in rabi season respectively); a structured design (with canals below <u>structured</u> level ungated and distributing water in proportion to area); and a time-bound schedule below the outlet (warabandi) providing each farmer with the full flow in the water course for a turn proportional to land holding (Malhotra, 1982, Reidinger, 1980[6]).

Schemes under the *Bengal Act* (o.a. Bihar) are typified by higher duties based on a design cropping pattern; a regulated canal system to distribute variable flows to the outlet; and informal farmer arranged schedules or field-to-field irrigation below the outlet depending on local conditions (e.g. paddy or non-paddy).

Irrigation in the West **<u>can</u>** be designed for proportional division since surface water is (almost) always wanted. Irrigation in the East **<u>must</u>** be responsive since need varies greatly. This has, Berkoff argues, decisive implications for management and for the efficiency of water use.

Farmers <u>in the west</u> know what to expect in terms of water, and therefore maximize returns to water rather than land. He plants only part of his holding to water sensitive crops, and gambles for the remainder (the 'scratch' crops), hoping that some water

6 The Reidinger article was first published in *Economic Development and Cultural Change*, 1974, 79-104.

becomes available from incidental rainfall or from pumps if that is affordable. The irrigation supply, however, is his life-line. The system is stable and self-policing as every next farmer with a 'water turn' acts as policeman on his predecessor in the turn, and will be policed by the farmer next in line, for not extending the period during which the farmers have rights to the full flow. It is a system of water distribution based on administratively designed and legally enforceable rights to individual land owners and no water user's association is needed (even if it were socially possible) to distribute the available water.

In contrast, farmers in the east plan primarily on expected rainfall. In a good year, crops need no irrigation and excess water can do great harm. In a bad year, the **whole** farm needs water. In principle, as in the west, part of the farm could be planted to high value crops with the balance rainfed. But the difference between high and low input crops is much less and, in a drought, head-enders have so much to gain from water theft (to save their standing crop) as tail-enders to lose.

A transformation of irrigation goals then tends to take place. The initial function of irrigation is as a 'stand-by' facility for drought (low rainfall) years. In times of rain water shortfalls conflicts among neighbours can be minimized by enlarging/adding outlets in the head reaches, which actions will deprive tail-enders of water. These emergency-borne new patterns tend to stabilize if head-enders are determined in resisting protests from more distant tail-enders. With enlarged outlets, head-enders will then grow paddy instead of 'design' or scheduled crops (thereby increasing returns to land), become more resolute to reject tailenders' demands because of the greater water sensitivity of paddy to water stress compared to other 'design' crops, and a vicious circle is established. Widely varying demand in the command area results therefore in an unstable and uncertain system with endemic farmer intervention in irrigation structures leading to destruction of minor irrigation works. Since tail-enders cannot risk failure due to drought, they are forced to plant low input crops in all years and fail to make productive use not only of irrigation (if there is water reaching them) but also of rainfall. Thus, such systems face the combined problems of paddy at the head, tails unirrigated, endemic farmer interference and extensive physical damage. The designed cropping patterns are discarded by both head- and tailenders.

Berkoff (1990, 7-12) argues that the relative irrigation performance in the four schemes studied is largely a function of rainfall (volume and variability). If rainfed cropping is viable, as in the Centre and East, farmers cultivate their full farm, even if schemes are designed for a lower (irrigation) intensity. This greatly complicates management since, in a drought, all crops need water irrespective of whether they are authorized for irrigation or not, while if it rains no water may be needed even for authorized crops. In contrast, if rainfed cropping is marginal, as in the West, farmers must plan their activities in expectation of irrigation rather than rainfall. Since irrigation is more predictable under warabandi, demands are stable and management is greatly simplified.

For the reasons indicated, improved irrigation management is inherently more difficult in the East than in the West of the Indo-Gangetic plain, and the first step is to **gain control** since otherwise no management is possible. But to achieve control, trade-offs may be necessary between the detailed ability to respond and manageability. Since water is scarce relative to land, the objective must also be conjunctive use defined as the optimum use of surface water, groundwater and rainfall under conditions where the only significant practical public intervention is the way that water is distributed in time and space in the surface system (ibid. iii). Thus the problems of determining irrigation objectives are intricately linked with the question of whether and/or how management control can be (re)established, in situations where apparently the authorities have lost control over the years under the impact of the forces as described.

Surface irrigation and groundwater

Where groundwater is available, accessible and of acceptable quality (non-saline), groundwater resources can in principle be combined to augment water resources available for agricultural production. A suitable groundwater aquifer may be visualized as a giant sponge that is buried underground, and does not suffer from water losses due to evapo-transpiration as do reservoirs behind dams and conveyance losses in water transport to fields and root zones of crops. It may be exploited within the limits set by safe yields, e.g. when not exceeding natural aquifer recharge. Options for conjunctive groundwater use can be visualized as in Figure 6 (Carruthers and Stoner[7], 1981, 13)

To start the discussion we provide some information on relative orders of magnitude of effectively used surface water and groundwater in agricultural production, and on the resulting apparent transformation of initial surface irrigation system objectives, to bring out the issues involved.

Basu and Ljung (in O'Mara, 1988) analyze a traditional surface irrigation system in India for which actual performance of fifteen years had deviated significantly from the original objectives of the project: total canal system efficiency was only 20 percent. However, the area is underlain by both shallow and deep aquifers, and the increase in recharge through leaks in the canal system has induced a secular rise in the water table (for the shallow

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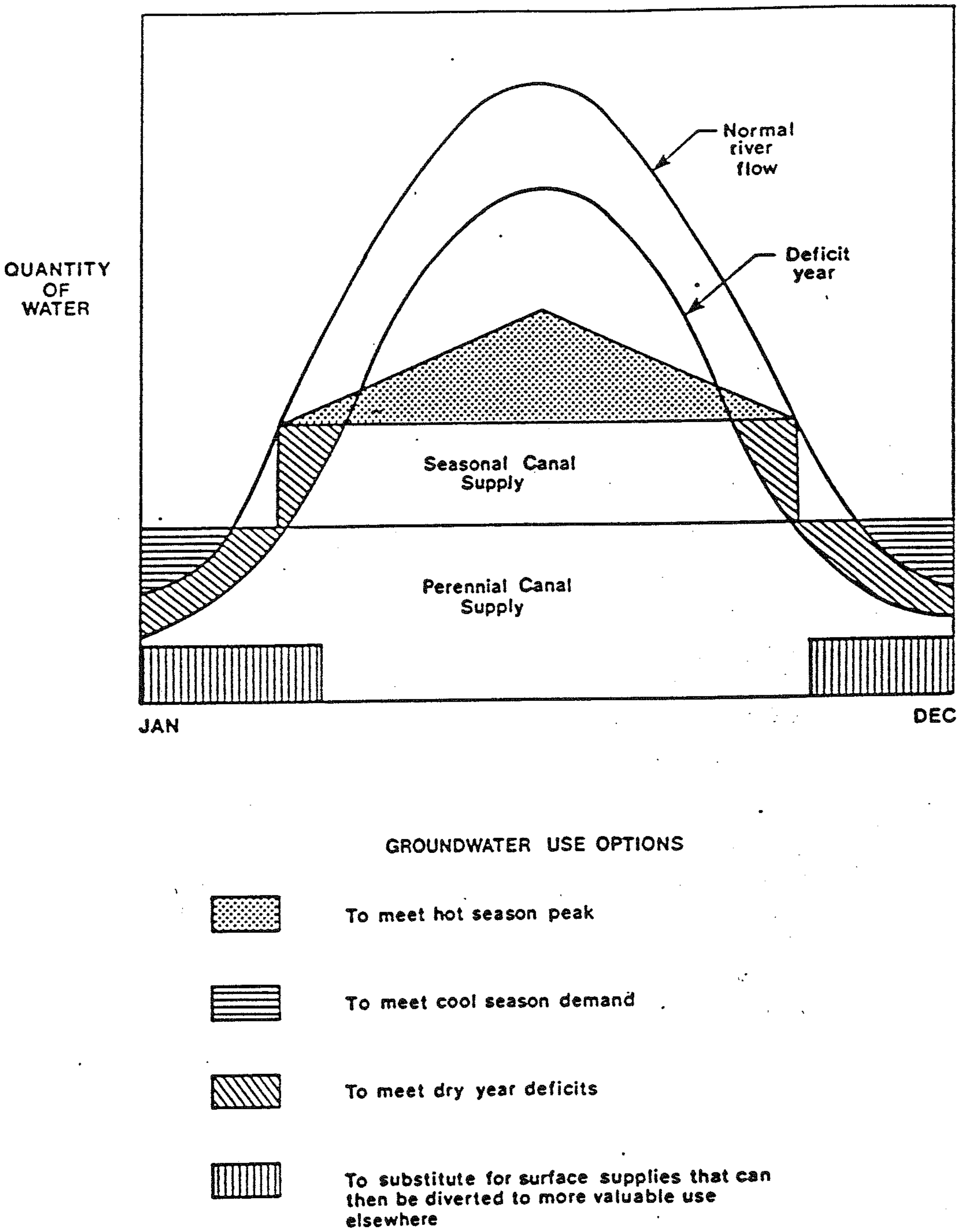
7 It may be pointed out that this paper by Carruthers and Stoner was initially prepared as a background paper for preparation of a *Bank Policy Paper on Irrigation*. However, to date the Bank has not been able to produce a first comprehensive policy paper on irrigation, a revealing omission considering that on nearly all major sectors of World Bank involvement it has over the years produced, at least one, and in some cases two such papers, often with quite different emphasis to reflect the Bank's own learning processes, cf. Forestry (1978, 1991), Education (1974, 1980, with additional separate papers on Primary Education, 1990, and Vocational Education, 1991) and Health (1975, 1980).

Figure 6. Groundwater use options



Source: Carruthers and Stoner, 1981, 13.

aquifer) of 0.14 meters per year. With a current depth to water table of 6 to 16 meters, a number of farmers installed shallow tubewells as the rising ground water table has now come into reach at acceptable cost for increased profitability of farming; an estimated 44 million cubic meters (MCM) were pumped annually, about 30 percent of estimated gross additions to aquifer storage. With median canal head releases of 230 MCM yielding only an estimated 46 MCM at the root zone, it is evident that water utilization was significantly conjunctive. But important issues of relative efficiency and distribution of ground and surface waters are involved.

On the basis of preliminary hydrological balances an additional 50 MCM of groundwater could be extracted within the safe yield of the shallow and deep aquifers. Basu and Ljung then projected the exploitation of the deep aquifer from a battery of deep **public** tubewells, whose discharge would be to the existing canals, and the institution of a programme of incentives to encourage farmers to exploit the shallow aquifer.

Before intuitively accepting the analysis and policy prescription, let us look at longer term developments in Pakistan, and to contrast some of Pakistan's institutional and managerial experience with what appears to be recommended for the scheme in India. The secular rise of the groundwater table in the Punjab is illustrated in Figure 7 (Johnson, 1988, 61)

Before the development of canal irrigation in the 19th century, the groundwater hydraulic system was in a state of dynamic equilibrium, with recharges balancing discharges over long periods of time. With low rainfall, infiltration of river water was the dominant source of groundwater replenishment. Irrigation through the canal system introduced additional sources of recharge in and around irrigated areas. Seepage losses were greater near the bifurcation points in the upper parts of the *doabs* (inter-river plains) because of the greater density of canals, and less near the rivers because the water table was already close to the surface.

To combat waterlogging and salinity a series of Salinity Control and Reclamation Projects (SCARP) were initiated from the early 1960s. **Public** tubewells were installed, but no provisions were made for enlarging the main water course channel and distribution system even though they were expected to carry two to three times the previous flow quantity. SCARP performance has been problematic. Frequent electric power rationing limited pumping to less than 50 percent of planned utilization. Poor maintenance and corrosion shortened the life expectancy of the pumps by two-third, from 40 to 12 years. The average water course channel losses on unimproved water channels varied between 10 to 15 percent per 300 meters of length. Half the initial flow would thus be lost after 1500 meters from the head of the watercourse, and such large losses imply critical shortages to farmers.

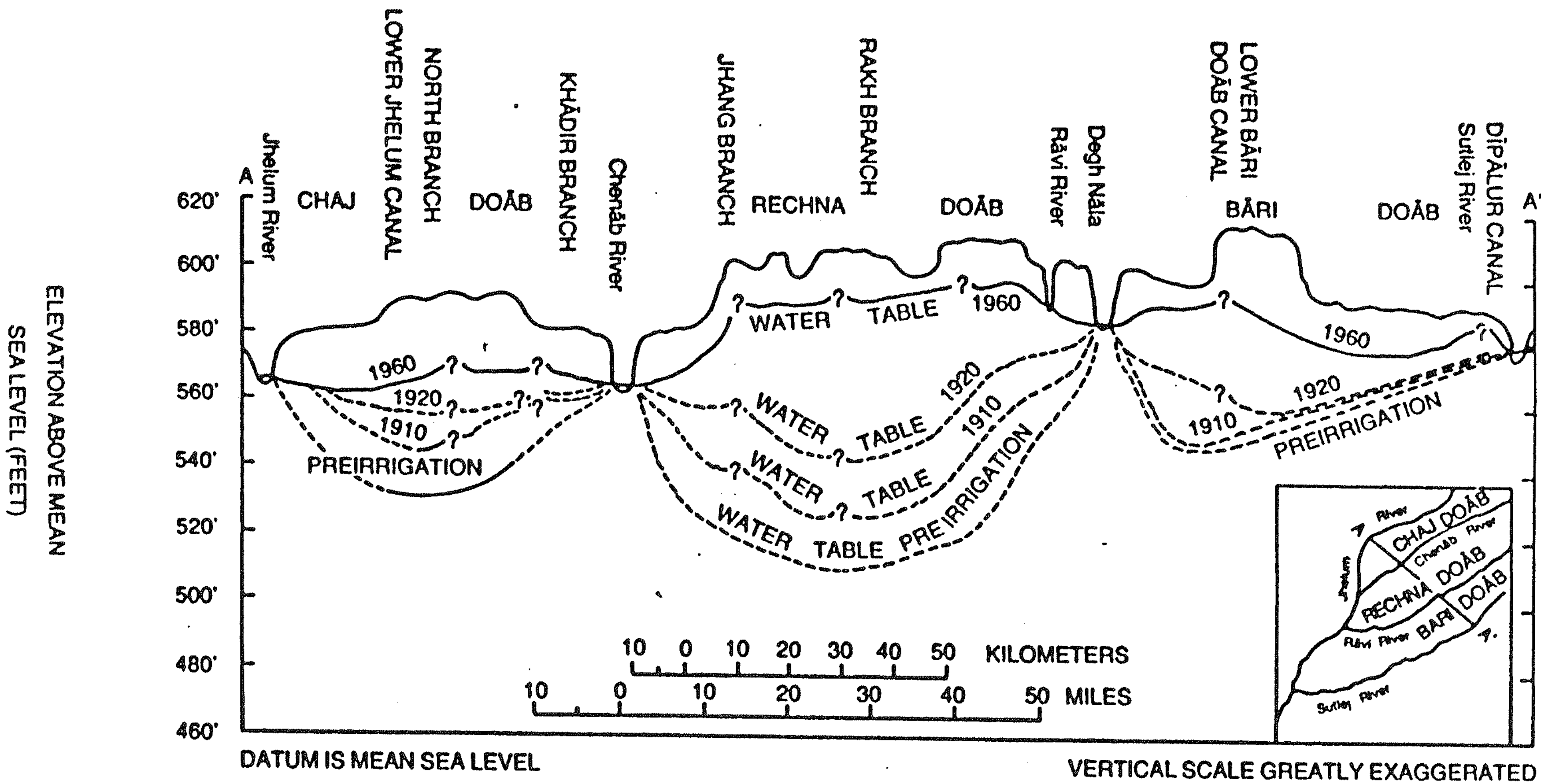


Figure 7 Water table profiles, Chaj, Rechna, and Bari doābs (D.W. Greenman, V.M. Swarzenski, and G.D. Bennett, 1967)

Source: Johnson, 1988, 61.

Despite the development of SCARPs, there has been no real change in the amount of land with high water tables over the past 20 years. Though SCARPS have played an important role in demonstrating the potential for groundwater development, private tubewells have actually pumped more groundwater than have public tubewells. WAPDA has conceded that most of the reclamation of salt-affected land in the past 15 to 20 years has been the result of improved water supply and individual farmer initiative, rather than sustained public programmes (WAPDA, 1979, cited in Johnson, 1988, 73).

In contrast to the elaborate models developed to determine if vertical tubewell drainage would be successful in the Indus Plain, little effort seems to have been spent, according to Johnson, on identifying **how** SCARPs should be operated and **by whom**. What might be lessons from Pakistan for the policy recommendations derived from the Basu and Ljung study discussed earlier for the scheme in India?

More than 3 million hectares of land in Pakistan are served by SCARP tubewells with a sunk cost of more than $500 million. Unless the government can locate and invest vast sums of money to replace and rehabilitate the SCARP systems, these systems are inevitably going to deteriorate. Private tubewells will be built where the groundwater is of good quality and markets are available for increased outputs. But since SCARP tubewells are located at the head of the watercourse to augment available flow to in principle all water course users, while private tubewells are located down the channel and close to the owner's fields, distribution losses are considerably higher for SCARP tubewells.

In saline water zones farmers find no incentives to install tubewells. Necessary drainage requires large-scale outlet channels to remove saline effluent, although freshwater skimming wells can serve a drainage role in some areas. Since drainage does not generate significantly higher incomes, but merely prevents degradation of existing incomes, farmers are reluctant, if not incapable, to pay much to support public drainage schemes. The result may be a sharp contraction in the area under effective irrigation.

It should be clear from the above that a mere hydrological analysis is only a necessary first step in the analysis of contemporary irrigation problems of the conjunctive use of surface water and groundwater, and to combat water logging and salinity but that a whole range of organizational, institutional, financial and micro and macro-economic issues will have to be explicitly addressed as well, **before** a policy line is set. But the agencies most knowledgeable about water are historically and professionally not equipped to deal with these issues, while outsiders often lack the detailed hydrological and irrigation knowledge to shape and influence the needed policy discussions differently[8].

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8 One might even ask the question whether there is sufficient exchange of information and sharing of experiences between different sections (countries and different professional perspectives) of the World Bank dealing with irrigation in South Asia.

The diffusion of tubewell technology

Historically, the development of the technology of surface water irrigation preceded that of tubewells based on compact diesel or electric power. In fact, the introduction of tubewells in the Indus Basin, and perhaps in the North China Plain as well, was motivated by concern over waterlogging and salinization, and the inexorable rise of groundwater tables (O'Mara, 1988, 2). The demonstration effect of public drainage wells set off a boom in tubewell investments by individual farmers (in South Asia) and individual communes (in China). In Pakistan, the number of tubewells increased from less than 5,000 in 1960 to more than 200,000 by 1980. In the Indian States of Punjab and Haryana, there were more than 400,000 wells (of somewhat smaller capacity than those in Pakistan) by 1980. It is estimated that more than 2 million shallow, small capacity private tubewells have been installed in the Gangetic Plain of India. In the 1960s and 70s more than two million small-capacity tubewells were installed in North China.

These massive investments in tubewells have completely transformed the use of water resources in these regions and raise problems of resource management that are beyond the grasp of existing irrigation bureaucracies. For example, in the Indus Basin of Pakistan tubewells now supply more than half of the water actually available for crop production in the fresh groundwater areas, but, of course, supply none of the water for crop consumption in the saline groundwater areas, which account for about one-third of the total irrigated land of the basin. In India, net irrigated area from wells began to overtake the area served by canals from the early 1970s (Easter, 1986, 74).

However, the bureaucracies concerned with the distribution of water do not attempt to achieve an efficient joint allocation of surface and groundwater supplies. In fact, the legal basis for doing so is unclear and open to challenge, as different legal regimes cover surface and groundwater resources and exploitation (Radosevitch, 1988).

From these trends one should also not conclude that future irrigation policy can best be left to groundwater development through private tubewell operators. Dhawan (1988, 17-19) argues that ardent proponents of groundwater irrigation in India need to realise a few hard truths: First, one has to take a flow, and not a stock, view of groundwater resources. One may add, that control over safe and not excessive groundwater use is difficult to establish and even more difficult to implement and police. Second, India's groundwater resources, being only about 30 percent of the total utilisable water resources of about 935 MCM, is much more limited than surface water. The differential arises because a smaller fraction of rainfall tends to infiltrate down to the groundwater table than the fraction which flows into the rivers. In arid areas, like Western Rajasthan, natural groundwater recharge amounts to about 1 percent of annual precipitation; in hard rock regions like the Deccan and Bihar plateaus, the percentage may be between 5-9 percent of annual rainfall; and in flat alluvial plains the percentage is about 20-22 percent. On the other hand, surface runoff may range between 20 and 60 percent of precipitation depending upon slope and vegetal cover of the land. It is the development of surface irrigation works that handsomely add to groundwater recharge. Hence, concentrating on the installation of wells and tubewells to the exclusion of canals and tanks in water scarce regions will create excessive pressure on groundwater resources.

The implication of the above seems to be that no matter how efficient or inefficient surface water currently functions or is to be developed, a major 'purpose' of these developments, in addition to spreading water inefficiently for agricultural production, is to supply groundwater through increased infiltration, which may then be more efficiently exploited because pumping can be attuned more precisely to agricultural needs. There is of course a potential barrier to this groundwater use in the cost of tubewells. But water users' cooperatives may overcome sometimes this disadvantage.

But India seems to be facing alo overall water shortages to meet future requirements. Investigation of water availabilities on a river basin by basin basis, and leaving aside the formidable technical problems of storing surplus water and transporting it to deficit regions, indicates that the areal coverage of the surplus basins is too narrow to generate enough surplus for the deficit regions. The data are presented in Table 19, and the time frame for water scarcity by states in Table 20. It is against this background also that the current problems and issues in the development of the Narmada River Valley, the largest and least-used river remaining in India, should be viewed.

3.2 Resettlement and crop choices

Large irrigation schemes with dams and canal systems always have major consequences for (re)settlement of people, because available waters are redistributed in spatial terms. To evaluate irrigation projects it is thus necessary to i.a. compare the benefits to people before and after irrigation development. In many cases, the *ex ante* cost-benefit analysis leaves out, or seriously underestimates important benefits to certain population groups before irrigation, thereby biasing the calculations.

River diversions for irrigation often have international as well as national implications. International, because rivers often run through several countries or because rivers form the border between countries. National, when different parts of the country receive the benefits, or bear the costs. Within India, irrigation development is a state and not a federal matter. Within Pakistan, conflicts between the provinces about the distribution of Indus Waters has been contentious ever since the creation of the state in 1947. Because of these implications of rediverting water resources spatially through irrigation 'beggar thy neighbour policies' are common.

Virtually the only major case where a successful international treaty could be concluded between states is the treaty on the division of the Indus waters between India and Pakistan after decolonization. It took some 15 years to negotiate, and the deal was accommodated by the willingness of international financiers such as the World Bank to

Table 19. Region-wise Absolute Water Scarcity/Surplus in India

Region/River Basin	Absolute scarcity* (per cent)
Region of Acute scarcity (-50%, +)	
Chambal	-71
Luni and others of Saurashtra and Kutch	-88
Yamuna	-67
Indus	-72
Godavari	-53
Krishna	-72
Pennar and other east flowing rivers between Krishna and Godavari	-64
Cauvery	-56
East flowing rivers below Cauvery	-66
Sabarmati	-78
Tons, Karamnasa and others between them	-53
Gomti, Ghaghara and others between them	-52
Tapi	-74
Narmada	-51
Mahi, including Dhadhar	-72
Regions of Medium Scarcity (between -20 and -49%)	
Son	-23
Right bank tributaries of Ganga east of Son	-26
Main Ganga including Ramganga	-27
Mahanadi	-27
East flowing rivers between Mahanadi and Godavari	-44
Region of Marginal Scarcity (less than -20%)	
East flowing rivers between Ganga and Mahanadi	-16
Gandak and other left bank tributaries	-14
Brahmaputra	- 2
Regions of surplus Water	
Barak and others	+91
West flowing rivers below Tapi	+40
For all rivers together	-48

* Annual precipitation minus Pan Evaporation

Source: M.C. Chaturvedi, 1976), cited in B.D. Dhawan, Irrigation in India's Agricultural Development, 1988.

Table 20. Approximate year when water demand in India will exceed ultimate utilisable resources, (by State).

State	1975	1980	1985	1990	1995	
		-80	-85	-90	-95	-2000
Punjab					X	
Haryana				X		
Rajasthan			X			
Gujarat		X				
Uttar Pradesh		X				
Madhya Pradesh			X			
Bihar					X	
Arunachal			X			
West Bengal		X				
Orissa				X		
Andhra Pradesh					X	
Tamil Nadu		X				
Kerala			X			
Karnataka			X			
Maharashtra	X					

Source: Carl Widstrand (ed), *Water Conflicts and Research Priorities*, Pergamon, 1980. p 55.

make available vast sums of moneys to finance link-canals and storage basins. In many other cases formal treaties cannot be negotiated at present and older treaties have been overtaken by events. One may think of the Farakka Dam between India and Bangladesh, or the current conflict over the Senegal River status between Mauritania and Senegal.

Of particular concern is the situation in the Middle East. Existing long-standing political conflicts extend to conflicts about water rights. The region is characterised by worsening general water shortages and by the fact that relatively large shares of water resources flow from neighbouring countries (Nile, Jordan, Euphrates). Relevant information is provided in Figure 8 and Table 21. (FAO/Netherlands Preparatory Conference for the Earth Summit, Brazil 1992). The Ataturk dam in South East Turkey has recently been completed but both Syria and Iraq complain that the water which Turkey intends to let go through (some 500m3/sec) is inadequate to meet the needs of these countries. The independence movement of the Kurds living in all three states complicates matters enormously, for if the Kurds would be successful they would effectively be in control of significant headwaters in the upper reaches of major irrigation rivers.

A somewhat different perspective is added when analyzing water conflicts between Jordan and Israel (Sexton, 1990). Both countries overestimated aggregate water availability from the River Jordan, so there is less to share due to physical scarcity. Next, both countries adopted water policies aimed to maximize irrigated area for agriculture over other water uses. It is then inevitable that progressive water shortages are calculated from the 1970s, and solutions are sought in the costly desalinization of sea water to augment water supplies. However, both countries are facing marketing problems in disposing of surplus agricultural products and this calls into question the very wisdom of continuing to base water use on the absolute priority to give water to the agricultural sector, even in the face of agricultural overproduction. Thus international conflicts over water distribution have direct ramification for internal development strategies to be pursued.

A third problem area is the division of the Nile river waters between civil war-torn Ethiopia, Sudan (North vs. South) and the role of the Jonglei canal, and Egypt (Waterbury, 1979, and Collins, 1990).

In reviewing national irrigation scheme proposals three aspects are of paramount importance: the (net) settlement effect, the (net) production effect, and the changes in legal and access mechanisms.

Table 21. Water resources in the Near East

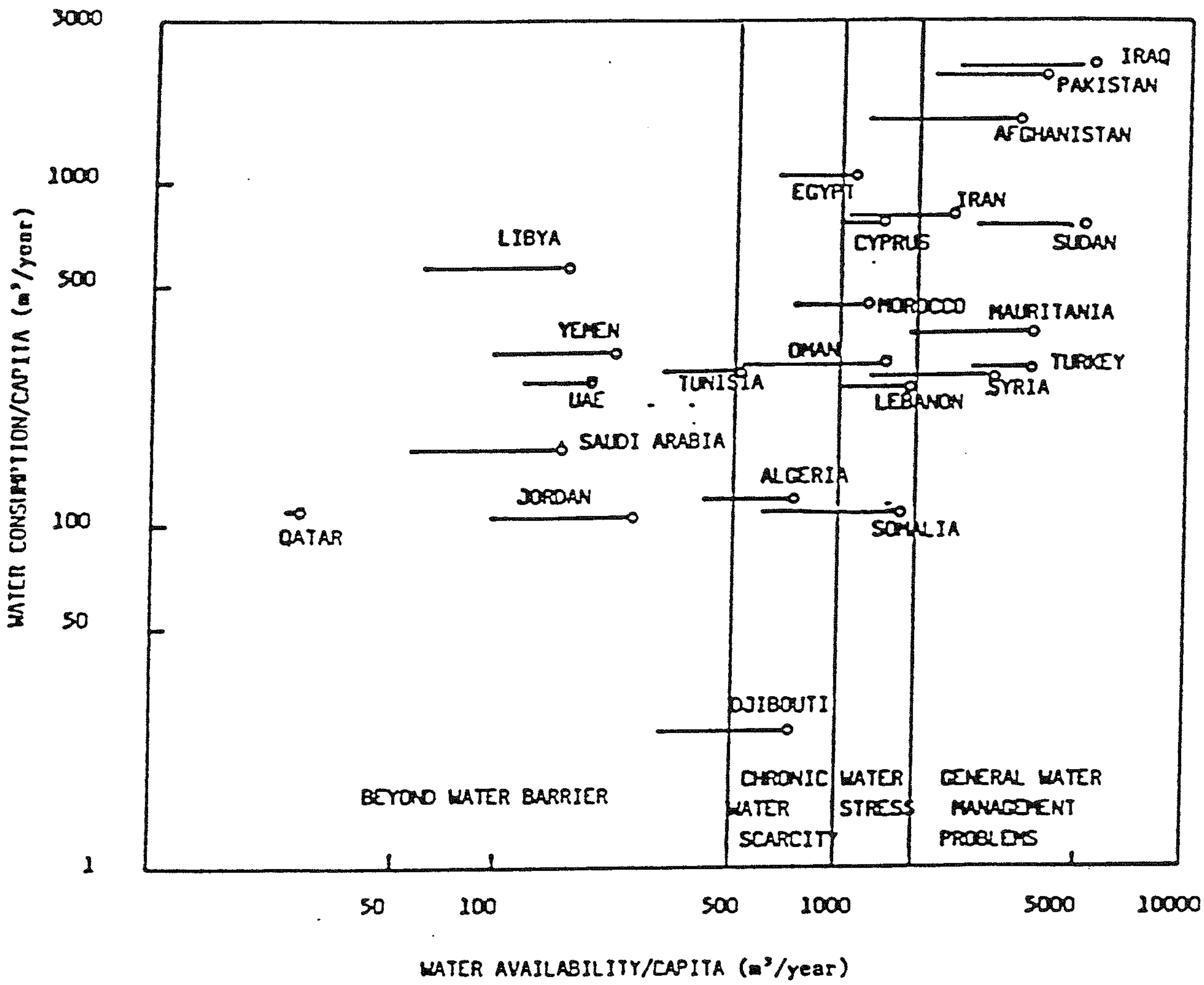
Country	Water availability: Internal	Water availability: Flow from outside	Water availability: Total	Total withdrawn	Percent in Agric.
I. High-income countries					
Bahrain	0	0	0	0	4
Kuwait	0	0	0	0.01	4
Qatar	0.02	0	0.02	0.04	38
Saudi Arabia	2.2	0	2.20	2.33	47
UAE	0.3	0	0.30	0.42	80
II. Middle-income countries					
Algeria	18.9	0.20	19.20	3.00	74
Cyprus	0.9	0	0.90	0.54	91
Iran	117.5	-	117.50	45.40	87
Iraq	34.0	66.0	100.00	42.80	92
Libya	0.70	0	0.70	2.62	73
Oman	2.0	0	2.0	0.43	94
Egypt	1.8	56.50	58.30	56.40	88
Jordan	0.7	0.40	1.10	0.45	65
Lebanon	4.8	0	4.80	0.75	85
Morocco	30.0	0	30.00	11.00	91
Syria	7.6	22.90	35.50	3.34	83
Tunisia	3.8	0.60	4.40	2.30	90
Turkey	196.0	7.00	203.00	15.60	58
Yemen	2.5	0	2.50	3.40	94
III. Low-income countries					
Afghanistan	50.00	-	50.00	26.11	99
Djibouti	0.3	0	0.30	0.01	51
Mauritania	0.4	7.00	7.40	0.73	84
Pakistan	298.0	170.00	468.00	153.40	98
Somalia	11.5	0	11.50	0.81	97
Sudan	30.0	100.00	130.00	18.60	99

Source: WRI (1990)
0 = zero or less than 1 cubic km per year
Figures do not include water produced by desalination plants in some countries

Water Resources in the Near East
(FAO/Netherlands 1991, Regional Document 4: 25)

Source: ISS/WWF.

Figure 8. Trends in water availability and needs in the Middle East



Water Resources Availability and Needs
(FAO/Netherlands 1991, Regional Document 4: 31)

Source: ISS/WWF

Where irrigation is of long standing it is often not possible any more to compare a 'before' and 'after' situation, and at any rate trends set in motion over a century ago have since transformed the national context beyond recognition. There is for instance a debate about the origin and impact of canal irrigation in India by the British and what pre-existing irrigation systems may have been stifled or overtaken by that development (Whitcomb, 1982, Stone, 1984, Sengupta, 1991).

Only for more contemporary schemes is it possible to provide information comparing the before and after irrigation situation, and these are more relevant for current and future decision-making.

3.2.1 Net settlement effect

The creation of dam lakes involves the removal of people who's lands will be inundated. Large dams imply large scale displacements as is illustrated in Table 22 and Table 4. When more dams are to be constructed in future and in more densely populated areas, the net settlement effect may well turn out to be zero or negative in that more people are kicked of the land than will later on benefit from irrigation development downstream. The Narmada River Dams and the Mahaweli project experiences in Sri Lanka are indicative of problems of newer dam development projects.

There are no historical experiences where adequate compensation and resettlement of displaced persons has taken place. Where often colonial governments, having used *Regal Doctrine* more than a century ago, claimed all unoccupied or unused land as crown land, and where independent states became successors to the colonial legal regimes, it had the effects of making many local communities trespassers on their own ancestral land. On that legal basis compensation is neither owned nor due. Where some traditional land rights are recognised by governments, compensation is inadequate[9]: financial compensation is usually too little and too late, and subject to embezzlement and corruption in the implementation arrangements. Where compensation in land is nominally provided for, either the quantity or the quality of the lands are not comparable to what was to be given up, resulting in net loss of livelihoods. Adequate compensation and/or resettlement cost tend to be large and thus have a measurable effects on the C/B analysis, which often already turn out to have been generally overoptimistic.

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9 It has been reported that the Staff Colony for the Sardar Sarovar Project on the Narmada in India has already cost more than the entire budget for resettling the 67,000 people who will be uprooted by the dam (Alvares and Billorey, 1987, 63).

Table 22. Resettlement of people owing to the construction of selected dams in the ESCAP Region.

Name of project, completion date	Country	Number of people relocated.
Bhakra, 1963	India	36,000
Damodar(4 projects,1959)	India	93,000
Gandhi Sagar	India	52,000
Lam Pao	Thailand	30,000
(11 proj.1963-71)	Thailand	130,000
Nam Ngum, 1971	Lao PDR	3,000
Nam Pong, 1963	Thailand	25-30,000
Nanela, 1967	Pakistan	90,000
Pa Mong (projected)	Thailand/Lao	310-480,000
Tarbela, 1974	Pakistan	86,000
Upper Pampanga, 1973	Philippines	14,000

Source: A.K. Biswas, *Impacts of hydroelectric development on the environment*, Energy Policy, Dec. 1982, p. 349, cited in *Water Resources Development in Asia and the Pacific. Some Issues and Concerns*, UN ESCAP, Water Resources Series No 62, Bangkok 1987.

Though, for instance, the World Bank has, since 1980 *Guidelines for Involuntary Resettlements*, experience shows that their application in hydro-power projects still has to be contested within the Bank itself. Moreover, the Bank faces major problems in having impact on governments unwilling to implement such policies. The much increased international attention for the plight of indigenous people above a proposed dam site is somewhat surprising and also selective, as the large numbers of people who have to abandon their land downstream as a result of failing irrigation resulting in salinity and waterlogging in 'middle aged' existing irrigation projects do not lead to similar widespread discussion about providing compensation in some form.

3.2.2 Net production effect and crop choices

Prior agricultural production in the dam lake site is usually underestimated and agricultural production increases downstream are usually overestimated. Where 'modern' irrigation is newly to be introduced, both irrigation skills and new crops and crop response characteristics are not sufficiently known to the new beneficiaries, without a major effort at education and extension, and in many cases without a major effort to organise transport, agricultural input supplies and output marketing arrangements. This implies higher costs and a slower accrual of project benefits than foreseen from increased agricultural production. Particularly in Africa these broader but necessary and complementary infrastructure facilities do not exist or are only very slowly forthcoming, compared to the situation in most Asian countries. Current donor policy preferences for privatisation of comprehensive government-owned and run irrigation development project authorities in many cases leads to hasten the collapse of already weakly performing projects.

Consider, for instance, the following aspects of the Bakalori and Dadin Kowa Irrigation Projects in Northern Nigeria, being developed since the late 1970s (Bird, 1983). At Bakolori, the land area lost under the reservoir is approximately 7,200 ha, the irrigation area covers 30,000 ha gross, but at least 25 percent of this is lost under permanent works. In addition, studies indicate that up to 20,000 ha of riverside land downstream is now seriously loosing its productive capacity, as waters previously used are now diverted into the irrigation area; and the dam attenuates the peak floods which before kept the riverine lowlands wet throughout the dry season, in support of agriculturalists as well as (semi) nomadic populations engaged in livestock. Put simplistically, 34,700 ha have been lost to cultivation in order to irrigate 22,500 ha. The increased production required from irrigation to compensate for this land loss is mind-boggling, irrespective of the project construction cost (350 million Naira). Often, different, and high valued crops for urban consumption are being substituted for traditional subsistence crops, to justify high investment cost and to rationalise government development efforts in irrigation.

The situation at Dadin Kowa is even less favourable with a reservoir of 35,000 ha displacing 23,000 people, and supplying an irrigation area of 25,000 ha. Some of the irrigation area is densely populated as 12,000 people have already been resettled into it (in the early 1980s), following the flooding of their land and homes by the Kiri Dam further downstream. Things are made worse by the fact that very few projects have had representative pilot farms set up before-hand, and very few have had adequate baseline socio-economic surveys carried out. The Bakalori Final Report (Impresit, 1974) used a sample of 41 unrepresentative farmers for an area of 30,000 ha. The report also badly misjudged the percentage of the project area occupied, assuming 60 percent occupancy, when even a brief glance at the 1962 air photographs indicates the figure to be nearer 95 percent (Bird, ibid).

3.2.3 Administrative arrangements

Planning and executing new irrigation projects always involves complex and far-reaching changes in administrative arrangements, ranging from changing land and water laws, to acquiring land to be inundated and allocating newly developed lands to future occupants. All these issues are highly contentious for planning and even more during implementation, when many of those affected hear for the first time about projects having been envisaged in planning bureaus elsewhere.

Water laws are complex. In many areas the influences of different legal traditions exist side by side. Major forces have historically been: indigenous laws, Roman Law, British common law and islamic laws (FAO 1973, 1978 and 1979). The geographical spread of these different traditions is illustrated in Figure 9.

Irrigation development requires the consolidation of often confusing legal structures to enable settlement patterns planning in the irrigation areas. It is important to know how legal water rights are being established and assigned, and how conflicts are adjudicated. Contentious issues are for instance: whether rights to land and rights to water can be separately held by different individuals or groups, whether temporary water rights are recognised such as those between agriculturalists and nomadic peoples, how rights to land and water are acquired, and whose rights prevail among competing claims.

Displaced peoples from reservoir areas are rarely the main beneficiaries of newly developed irrigation capacity. The time lag between reservoir inundation and irrigation development is usually too long for the displaced low-income farmers to have survived. Where no income safety net can be provided, displaced persons have no option but to migrate or to find employment in non-agricultural activities. A minority may find work in irrigation works construction as unskilled workers. More often than not, the settlement authority establishes the right to allocate irrigated lands to prospective settlers, and this provides ample opportunity to exercise patronage to friends and politically favoured groups such a civil service personnel or the military. It is then probable that many such new rights holders will not farm by themselves but organise tenancies in various forms.

A general feature of irrigation especially in Africa is that governments, to avoid accusations of tribalism and to justify public expenditure, open up new irrigation lands to all citizens regardless of tribal origin or skills. This does not augur well for subsequent development in production, and in the longer term it will make it also much more difficult to organise irrigation communities or let them emerge spontaneously. The Government then finds itself in the position, whether by design intent or in effect, to maintain control over the irrigation project, and privatisation is doomed to fail. Thus, the study of the role of government and of the settlement recruitment process can provide rich information to assess possible or probable developments in planned or completed projects (The case of Bura Irrigation project in Kenya is richly detailed in De Leeuw, 1985).

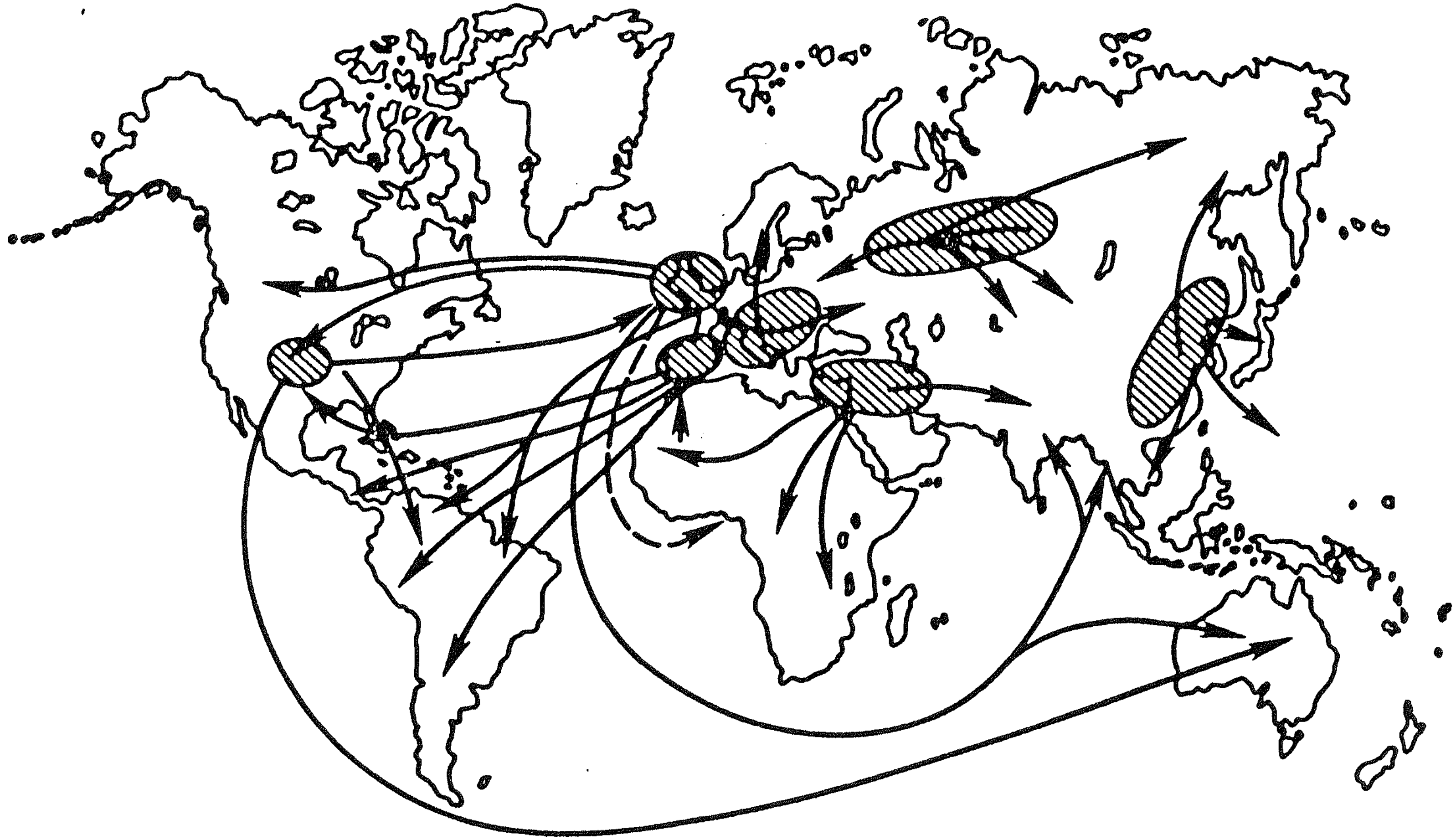


Figure 9. A descriptive map of major legal systems ([hatched box]) and their variations or paths of influence (→)

4 IRRIGATION AND PUBLIC HEALTH

4.1 Public health implications of irrigation

Many diseases are linked to water and water use. Hence, water resources development policies, whatever their positive effects on mankind in terms of protecting against floods and enabling increased food production, they run the risk of stimulating the development of waterborne diseases with negative effects on public health. One may therefore expect there to be a direct correlation between the introduction of irrigation and the incidence of diseases. The most common diseases generated by irrigation are vector-borne diseases. Some figures on the importance of various forms of waterborne diseases and of the increased incidence of infections in the wake of irrigation are given in Tables 23, 24 and 25.

Table 23. Principal Sources of Disease

Disease (common name)	Persons Infected	Controllable with Clean Water Supply & Basic Sanitation
	(millions)	(percent)
Acquired in Drinking or Water Contact:		
Cholera	na	90
Typhoid fever	na	80
Diarrhea	500	50
Guinea Worms	na	100
Schistosomiasis	200	10
Acquired in Collecting Water:		
Malaria	300	na
Sleeping Sickness	na	80
River Blindness	20-30	20
Elephantiasis	270	na
Acquired by Contact with Excreta:		
Roundworm	650	40
Whipworms	350	na
Hookworms	450	na

Sources: *Safe Water and Waste Disposal for Human Health: a Program Guide*, U.S. Agency for International Development, 1982;Zoonoses and Communicable Diseases Common to Man and Animals (Washington, DC, Pan American Health Organization, 1980), cited in: William U. Chandler, *Improving World Health: a Least Cost Strategy, Worldwatch Paper 59, July 1984.*

Table 24. Compound growth rates of water-borne diseases in selected states of India.

State	Cholera	Dysentery	Malaria	Filariasis
Andhra Pradesh	-15.6	5.1	-3.0	12.8
Karnataka	4.1	12.8	-5.8	-3.0
Madhya Pradesh	11.6	2.0	7.3	-2.0
Orissa	-3.0	23.4	13.9	11.6
Rajasthan	1.0	4.3	17.4	1.0
Uttar Pradesh	3.1	6.2	-23.7	9.4

Source: Joshi, P.K. and A.K. Agnihotri, An assesment of the adverse effects of canal irrigation in India, IJAE 1984 Vol 39.3.

Table 25. Changes in schistosomiasis incidence following implementation of water project.

Country	Project (Yr completed)	Pre-project prevalence (percent)	Post-project preevalence (percent)
Egypt	Aswan (first 1900)	6	60% (3 years later)
Sudan	Gezira Scheme (1925)	0	30-60% (15 yrs later)
Tanzania	Arusha Chini	low	53-86% (30 yrs later)
Zambia/ Zimbabwe	Lake Kariba (1958)	0	16% adults (10 yrs 69% children later)
Ghana	Volta Lake (1966)	low	90% (2 yrs later)
Nigeria	Lake Kainji (1969)	low	31% (1 yr later) 45% (2 yrs later)

Source : FAO (1986), African Agriculture: The next 25 years, Annex 2, the land resource base, p.69, cited in Jon R. Moris and Derrick J. Thom, Irrigation Development in Africa. Lessons of experience. Boulder (westview), 1990.

There is no need in this paper to describe the major waterborne diseases and their epidemiology in detail, as this can be found in any medical text. An excellent and concise description and analysis of vectors in transmission is found, for instance, in Oomen et.al (1990). A summary of vector infection and major diseases is given in Table 26 (Oomen (1990, 36).

4.2 Incorporating public health in irrigation designs.

In the past, the study of public health issues linked to irrigation development has not received much systematic attention. In fact, there are still many new projects where these aspects are not at all or only cursory dealt with. Only in 1990 has a textbook become available which treats the linkages between environmental health engineering and irrigation design in a systematic way. The book (Oomen et.al. 1990) is based on a longer term (5 year) project of collaboration between irrigation engineers from the Netherlands and WHO, and much of this section is derived from that source.

The incorporation of preventive measures, or of designing remedial strategies, usually fall in different domains of government policy making and implementation machinery, and this may help to explain this neglect for public health in irrigation design. Specifically, preventive measures will be part of project costs and within the budget of the Irrigation Authority, while remedial measures are a burden to Departments of Health and/or of Rural Development or Internal Affairs. This state of afairs may contribute to the low priority often being given in irrigation planning to public health aspects of these interventions.

The emphasis in Oomen (1990) is on the technical possibilities of environmental engineering in irrigation designs. It will become clear that there are important implications for total system design, and therefore public health considerations ought to be included in initiatal project concepts. Preventive measures rather than remedial measures are stressed. In specific cases preventive measures may not be possible or feasible, and the only solution would then be to stress curative strategies after the diseases have gained a foothold or have spread widely in irrigation areas.

A general conclusion emerging from the discussion of technical measures to improve irrigation design from a public health point of view, is that they all seem to require high levels of irrigation management and control for the measures to be effective. Moreover, many measures will only be effective if water supplies are reliable. Many public health measures loose their effect if water supply, for whatever reason, is irregular and farmers respond to this situation in irrrigation behaviour.

In most irrigation schemes insecurity and instability of water availability for agriculture is endemic and human behaviour will react by 'hoarding' water, which create health hazards. In addition, trade-offs exist between irrigation water use and, for instance, land

Table 26 Type of vector infection, diseases, and disease organism

Type of vector infection	Disease	Disease organism
Mosquito-borne	Malaria Filariasis Yellow fever Dengue Encephalitis Other arbo-viral infections	Protozoon Nematode Viruses (arbo viruses = arthropod-borne viruses)
Snail-borne	Schistosomiasis (bilharzia) Clonorchiasis Opisthorchiasis Paragoniamiasis Fascioliasis Fasciolopsiasis	Trematode Trematode Trematode Trematode Trematode Trematode
Fly-borne	African trypanosomiasis (sleeping sickness) Onchocerciasis (river blindness) Leishmaniasis (kala azar, oriental sore) Loiasis (various types)	Protozoon Nematode Protozoon Nematode
Miscellaneous		
Water flea	Dracontiasis (guinea worm)	Nematode
Bug	American trypanosomiasis (Chagas' disease)	Protozoon
Louse/tick	Plague, louse-borne fevers, and other fevers (tick-borne, mite-borne)	Bacteria, spirochete, rickettsiae

Source: Oomen, 1990

preparation costs: well prepared lands will require less water than poorly prepared lands. To collect standing water sources may be a rational farmer response to water insecurity or to reduce labour cost for land preparation, but at the same time such supplies tend to increase environmental health risks in irrigation situations. Moreover, while different, and from an environmental health point of view, desirable designs for future irrigation projects might be possible, cost considerations may inhibit them being implemented. In addition, it is not always clear whether already existing systems can be modified to better take account of modern insights from environmental engineering.

The present discussion shall remain limited to design features for dams, dam lakes and irrigation channels and works. The problems and issues of public health in human settlements in irrigation areas shall not be discussed because this would carry the present discussion too far. The practical problems of separating the different functions of water from different user groups are well known, and problems of cross-contamination, such as between water use for livestock and for human consumption, need not be discussed here.

In Table 27 a summary is given of disease transmission mechanisms and irrigation design features

Because the most common diseases generated by irrigation are vector-borne diseases public health engineering interventions are directed at the incorporation, where possible, of measures which aim to restrict the habitats for snails and insects as intermediate hosts.

4.2.1 Control measures in large reservoirs

Large reservoirs, such as the recently constructed reservoirs in Africa (Volta, Kariba or Kainji) are enormous solitary lakes. Flows out of these reservoirs cannot be manipulated beyond the direct requirements for irrigation and power. Nor can the flows into the rivers be controlled, being determined by upstream rainfall and runoff. Coupled with their extremely long shorelines, their reservoirs have basic characteristics which make it unlikely that environmental management methods (e.g. water-level fluctuations or the application of chemical pesticides) will be feasible for the control of insects or snails.

In contrast, smaller reservoirs, being part of a network of similar reservoirs on the same river system are well suited to environmental management. If water-management for insect or snail control is being applied in an upstream reservoir, a downstream reservoir can utilize any water lost from upstream. Even only two small reservoirs, forming the system, offer considerably more operational flexibility than one large reservoir.

Table 27.

Transmission mechanisms of diseases, and design components for environmental health engineering that contribute to integrated control

Design component	Transmission mechanism	Design feature	Related diseases
Occupation	Insect-vector breeding in water/ biting near water	Dam construction	Malaria, onchocerciasis, trypanosomiasis, other vector infections
		Irrigation network	
	Water-based	Agriculture	Schistosomiasis
Water supply	Water-borne	Quality and/or	Diarrhoeas & dysenteries
	Water-washed	quantity of water	Enteric fevers
			Enteric virus infections
		Quantity only	Skin infections
			Eye infections
			Louse-borne fevers
	Water-based	Protection of water source	Guinea worm infection
Excreta disposal	Person-person contact	Latrine construction	Diarrhoeas & dysenteries
	Domestic contamination	Excreta treatment	Enteric fevers
	Water contamination	Hygiene environment	Soil transmitted helminths
	Field contamination		Beef and pork tapeworms
	Crop contamination		Waterbased helminths (Schistosomiasis)
			Filariasis
Housing	Siting near vector habitat	Siting/screening of houses	Malaria, filariasis, onchocerciasis, trypanosomiasis
	Overcrowding	Space and ventilation	Epidemic meningitis
	Air pollution		Acute & chronic respiratory infections
			Respiratory malignancies
	Vector breeding	Water storage	Arbo-viral infections (dengue, yellow fever)
	Refuse	Refuse disposal	Chagas disease, leishmaniasis
	Construction	Construction materials	Soil transmitted helminths
	Fire	Burns	Fire hazards
Nutrition	Lack of calories	Staple crops	Undernutrition
	Lack of proteins	Home-gardens	Protein-caloric malnutrition
	Lack of vitamins		Vitamin deficiencies
	Food storage	Storage facilities	Food-poisoning: diarrhoeas
	Food preparation		
Energy	Use of fire-wood	Kitchen stoves	Food poisoning: diarrhoeas
	Open fire	Chimneys	Burns
	Storage of kerosene		see: Air pollution
Village infrastructure Health care		Immunizations	Childhood infections, poliomyelitis, yellow fever
		Mother-Child care	Perinatal/infant mortality
		Education and Communication	Treatment Endemic diseases: malaria, diarrhoea respiratory infections, helminths, schistosomiasis etc.
			Birth regulation

Source: Oomen, 1990, 27.

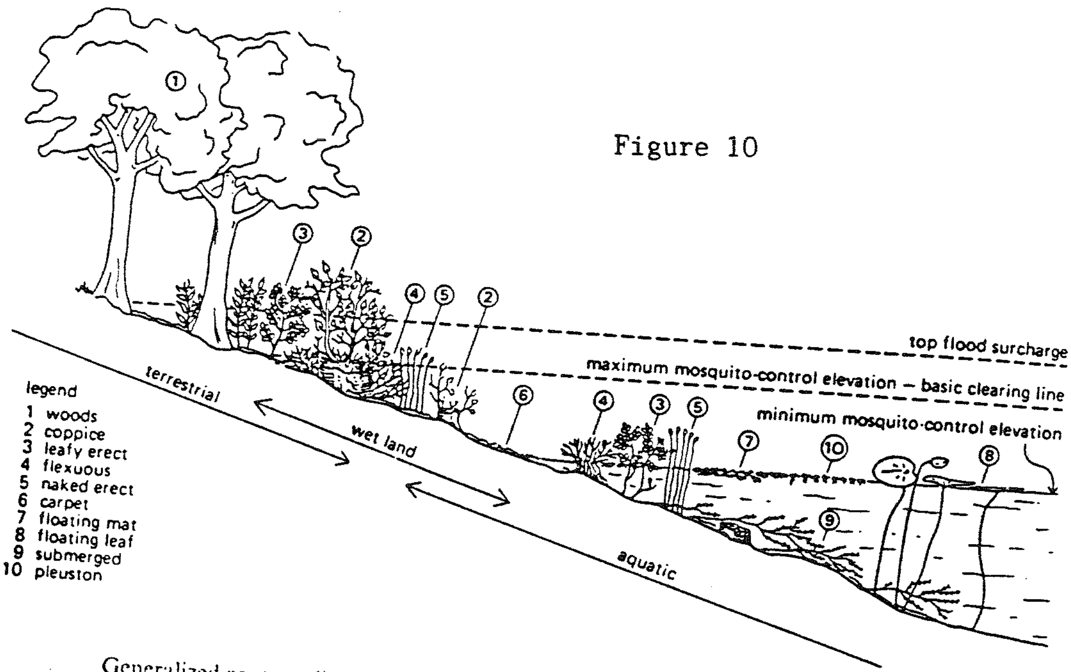
There are also fundamental differences between large natural lakes and large man-made reservoirs, as the former have reached greater ecological stability, with longer residence time of their waters and smaller annual fluctuations. This has important repercussions for the location of human settlements around the lakes, for shoreline characteristics, and for the habitats for snails and insects. Sharp seasonal fluctuations in the water level of man-made lakes leads to seasonality in the transmission of diseases.

The importance of shoreline characteristics follows from the fact that mosquitos depend on the combination of vegetation, air and water. Where plant parts intersect the water surface, breeding conditions for mosquitos are fulfilled. Similarly, bilharzia snails reproduce in areas of 'illuminated' shorelines, i.e.that portion of the shoreline at a depth less than the penetration of light. If the illuminated shoreline is flooded for significant periods during the season when water temperatures are sufficiently high for snail reproduction, suitable habitats will be created. Figure 10 and 11 (Oomen, 1990, 75 and 111) clarify these concepts.

Given these habitat characteristics, the rapid recession of the water level in a reservoir will strand floating debris and aquatic vegetation; it will strand and kill aquatic snails, and will strand mosquito larvae and also expose them to predation by fish. Water-level fluctuations in reservoirs can also be used for malaria control in the streambed below. Periodic high rates of discharge in the streambed when water levels are being lowered in the reservoir, flush the mosquito larvae out of their protected sites (Oomen, 1990, 114). For flushing out stream sections, the water course need not necessarily be a reservoir. A sudden release of water from an upstream section of a stream or canal can flush out a downstream section. Two forms of flushing can be used: (i) Stagnant pools in a predominantly dry streambed are flushed out by intermittent release from an impoundment; or (ii) A continuous flow, sufficient to allow mosquito breeding, is supplied with an extra discharge which then destroys the larvae. Sudden releases of water are converted into a turbulent crest of a wave travelling parallel to the streambed. The flush wave and the turbulence seem to be the operative factors rather than the velocity of the current.

For irrigation canals, the incorporation of flushing will engender problems (possible over-bank flows; interference with the normal water conveyance schedule; loss of water). Nevertheless, calculations of water requirements usually include a leaching component to prevent salinization. Why, then, should the calculations not include a 'flushing' requirement?

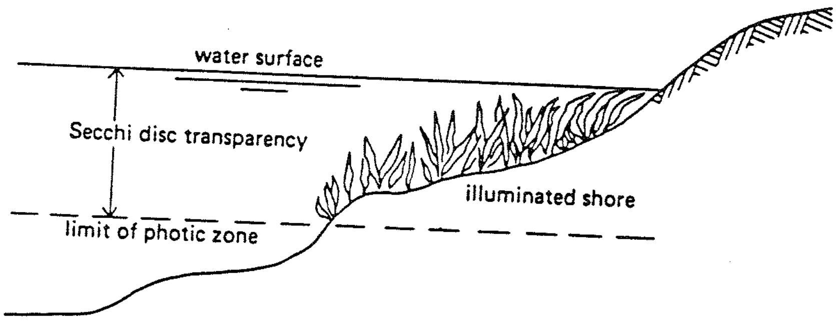
Figure 10



Generalized contour distribution of basic plant types on the shore line of a main-river reservoir (Source: Tennessee Valley Authority 1984)

Source: Oomen, 1990, 75

Figure 11



Definition of 'illuminated shoreline' in reservoirs

Source: Oomen, 1990, 111.

Various types of syphons to permit flushing can be built into the irrigation system. Regulatory or emergency spillways or outlet structures with shallow flows at high velocities need attention from a public health point of view because they may be especially suitable for egg depositions by black flies. Stepped spillways should be avoided; steeply inclined or vertical spillways are to be preferred, and the use of siphons or sluice gates to periodically dry out spillways could be effective to control disease vectors.

The technique of shoreline modification is applicable for both bilharzia and malaria control. It consists of straightening irregular edges by grading, and improving drainage by ditching and filling. Vegetation control, on the shore and in the canals, is also important for public health. A major question in preparing reservoir sites prior to flooding is whether to cut and clear trees and other vegetation below the reservoir's expected high-water line. This can be extremely costly in forested areas, but the benefits for public health lie in the reduced intersection-line. Shoreline modification and vegetation control may also increase the risks of bank erosion in reservoirs and canals, thus increasing sedimentation and reducing canal capacities. The control of aquatic weeds in irrigation canals requires considerable efforts for sustained canal maintenance. From the point of view of irrigation all canals need to be kept clear for the full length, to enable water to reach the tail ends of irrigation systems. From a public health point of view, the greatest dangers lie in those areas closest to human settlements. While the local population might be persuaded to regularly clean canals within its area of direct control, the capacity of Irrigation Departments to properly maintain control over aquatic weeds in the major canals is often in doubt. Such has been the experience in Africa, such as in Gezira, Sudan (Euroconsult, 1982), but also the infestation status of aquatic weeds in India is not encouraging, as is indicated in Table 28.

Table 28. Obnoxious aquatic weeds and their infestation status in India

Common name	Percentage showing infestation Increased	Decreased	Constant
Water hyacinth	66	7	26
Water lily	30	11	59
Florida eledea	38	14	49
Cattails	64	2	34
Duck weeds	57	5	38
Tape grass	38	19	43
Water lettuce	61	6	33
Water fern	63	6	31

Source : D.K. Biswas, Intregrated measures for control and utilization of aquatic weeds, Bhagirath, Vol 25 No 3, 1978, cited in: Joshi, P.K. and A.K. Agnihotri, An assesment of the adverse effects of canal irrigation in India, IJAE 1984 Vol 39.3.
[Table 28 : Aquatic weeds infestation status in India, WATAB]

4.2.2 Control measures in irrigation systems

Many tropical irrigation systems - with their networks of canals, regulating structures, intermediate storage points, and complementary drainage works - have become enormous aquatic habitats for disease-bearing insects and snails. Experience, however, has shown that diseases can be prevented primarily through canal design, crop selection, water management, location of housing and canal maintenance.

For most insects and snails, the local velocity of flow is an important determinant of habitat suitability, but in contradictory ways. Malaria and bilharzia are favoured by slow velocities, whereas river blindness is favoured by high velocities. Under ideal conditions small snails migrate upstream as far as 30 m/month, or between 300 and 400 m/year, and downstream as much as 2 km/year. Flotation and dislodgement by the snail itself could carry them as much as 20 or 30 km/day. So, in an irrigation canal of uniform cross-section with steady flow, one might expect considerable population movement. The First Law of Snail Control is therefore: 'The snails will always move in', because most new irrigation schemes in endemic areas are invaded by bilharzia snails within a year or two. The Second Law of Snail Control is that 'The snails always come back'. (Oomen, 1990, 138). The aquatic stages of stream-breeding mosquitos - the eggs, larvae and pupae - can be destroyed or dislodged by the water flow, and turbidity, though it is not well known what optimal design velocities are.

Older irrigation schemes often develop problems with siltation and aquatic vegetation in their canals, causing them to become favourable habitats for insects and snails. These conditions are especially prevalent in the tail-ends of systems and in the field channels. Even if a system was properly designed and initially operated with little or no siltation or vegetation, any expansion or intensification of irrigation beyond the original plan often leads to heavier irrigation flows during seasons when quantities of suspended sediments are higher, and to longer seasons of irrigation, thus giving time to develop larger standing crops of aquatic weeds. In canals originally operating 6 or 7 months in the year, there is ample opportunity for the natural control of weeds through desiccation, and also removal of weeds and silt is quite easy. If this schedule is eventually supplanted by 11 or 12 months of irrigation, weed growth becomes extremely dense and can, in itself, accelerate siltation. High nutrients in sediment, in turn, lead to further acceleration of weed growth.

In addition to flow velocity and vegetation, the main environmental factors affecting the distribution and dynamics of snails and insects are water temperature - higher temperature stimulating biological processes - and water clarity - high turbidity due to silt erosion reducing the numbers of snails.

There are three human activities that strongly affect the transmission of water-associated diseases: (i) human contact with irrigation and drainage water containing bilharzia snails; (ii) human contamination of those waters with faeces and urine; (iii) sleeping in areas unprotected from mosquitos during the seasons of malaria transmission.

Malaria mosquitos, tropical blackflies, and bilharzia snails can all be controlled with **efficient** drainage because they all depend on water to complete their life cycles. But it has been noted before (Section 3) that most irrigation projects in developing countries do not have adequate drainage, leave alone effective drainage, and investment in drainage is not popular due to high costs, and the required interference in rural social structures in already existing irrigation settlement areas. Moreover, drainage, from a public health point of view, is complex. The design time for drainage systems aimed at the breeding of mosquitos is the time between the deposition of eggs on the water surface and the emergence of the flying adult form. Recommended times are 2 weeks for malaria-control drainage.

If bilharzia snails are to be controlled by drainage, the approach is quite different from that for mosquitos. Rapid drying is helpful but the critical feature in the design is the time before re-flooding or re-submergence occurs. Long dry periods will kill a large fraction of the adult snails and all of the eggs and juveniles. The death of snails due to drying should be thought of in terms of half-life of survival. The half-life is the dry-ness in days for half of the population to survive. Research has shown that for some species half-life was only 15 days if species were stranded because of a sudden drop in water level, but increased to as much as 160 days if the drop in water level was slow because of natural evaporation and filtration. Long half-life periods mean that in irrigation schemes usually enough snails survive to revive the habitat (Oomen, 1990, 147).

For public health reason, as well for reasons of irrigation management and agricultural production, rotational distributions of water (such as warabandi) are to be preferred above continuous flow systems of water distribution.

When such measures as drainage, water distribution, canal maintenance, and crop rotation are introduced to control snails, they may have concomitant impacts on mosquitos or other disease vectors. Hence, a more comprehensive consideration of all these factors should lead to optimal and more feasible irrigation design.

Canal maintenance is important for irrigation and public health. While the negative effects of aquatic weeds have been stressed repeatedly in this paper, it should be realised that aquatic weeds also have their positive points. For fish, plant material is vital; it provides a hiding place from predator birds, acts as substrate for food organisms, and serves as a spawning place. The real problem then is the quantity control of aquatic weed growth through aquatic weed management.

Chemical control through herbicides is often forbidden due to toxic side-effects. Mechanical cleaning is often recommended above manual weeding, because of reduced exposure of humans to infested waters. Though in old systems mechanical cleaning is costly due to irregular and uneven river banks, and poor access. Biological weed control, for instance through grass carps which eat several times their body weight in greenery per day, and prevalent in parts of China, has been found difficult elsewhere such as in Egypt, because of problems in propagation and other impurities (human or chemical) in the water negatively affecting fish health.

Canal lining has many advantages: it increases water velocities, eliminates rooted growth, reduces seepage and thereby the need for drainage, facilitates the control of residual disease vectors, prohibits the snail vectors from sheltering, and it is an incentive for planning and constructing special bathing places for children and drinking places for cattle.

While the cost of lining are quite considerable and often prohibitive, one should also realise associated benefits, other than on public health. Canal lining leads to reduced cross-sections, leading to lower cost for land acquisition, less loss of land, less earthwork, smaller dimensions of structures and bridges and fewer structures. In flat areas, the opportunity arises of putting a larger land area under command, while maintaining a certain flow velocity; and, finally, less sedimentation and less growth of aquatic weeds reduces maintenance costs (Oomen,1990, 156).

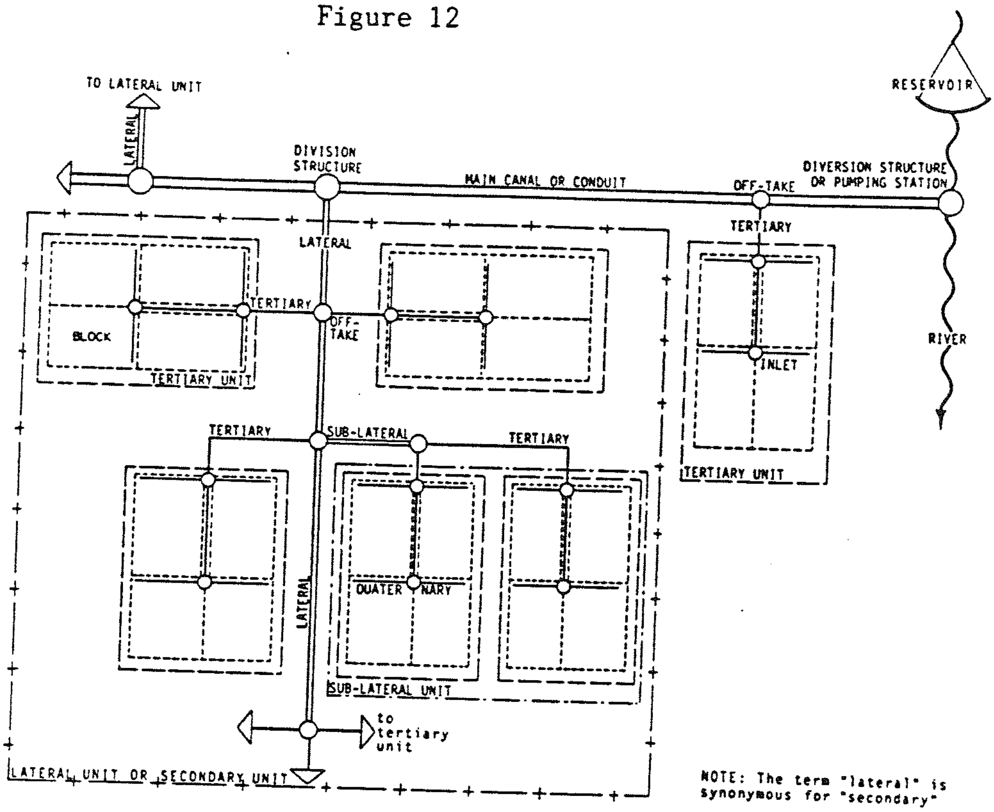
4.2.3 Control measures in farm water management

There are clear relationships between crops and diseases: sugar cane and bilharzia; cotton and rice and malaria; tea cultivation and endemic malaria and hook worm. In certain islands in the Caribbean, coffee cultivation has been associated with hookworm, and bananas with bilharzia. Before a vaccine became available for yellow fever, the disease was strongly connected with sugar cane, but in this case the mosquito vector was breeding in the clay evaporation pits used in the primitive processing of sugar. Because sugar is almost always irrigated and is usually cultivated continuously, it is not surprising to find strong links to bilharzia. In East Africa, a combination of rice irrigation and pest-control measures to combat rice-stem borers produced a double peak in malaria mosquito populations. Rice irrigation had the effect of extending the natural malaria season, after the rice had been transplanted in shallow muddy pools. A severe mosquito problem has occurred in rice cultivation in flood plains of the Yangtze and Yellow Rivers in China. Conventional control measures with pesticides were impractical and eventually a method of intermittent irrigation was applied to help deal with the mosquito problem (Oomen, 1990, 161-2).

In almost all of these associations between crops and disease, water is the common factor. The seasonal water requirements for rice, sugar and cotton are high, and irrigation systems able to provide large amounts of water for several months of the year are needed. Labour requirements are similarly high during part of the season and such populations often live in the area under conditions of minimal sanitation. Even if water requirements are modest, as for tea, coffee and bananas, conditions favourable to disease can develop. A similar disease hazard can occur when several crops are cultivated in rotation, giving rise to additional water and labour requirements.

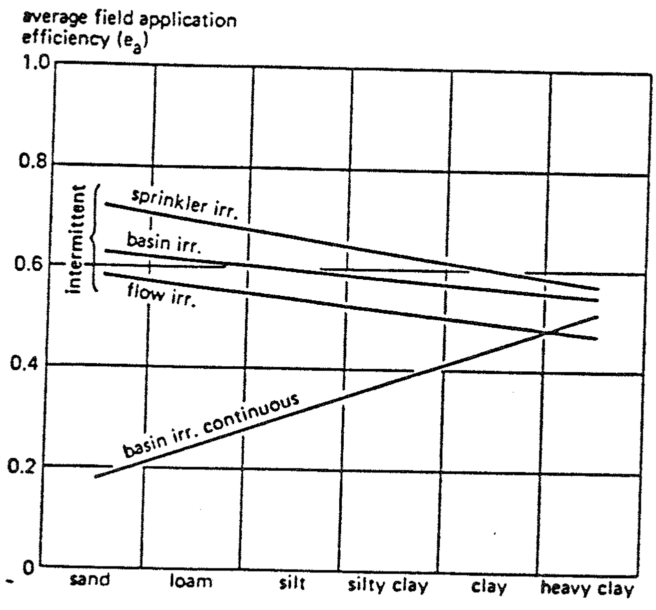
Farm water management takes place inside the tertiary unit which forms the heart of the irrigation system. At that level authority is often transferred from the Irrigation Department and associated bureaucracy to farmers and/or farmers organisations, and communications for bureaucrats to schedule water and for farmers to practice public health measures as well as cultivate crops efficiently is most problematic. At that level irrigation efficiency is generally very low but the issue should be taken very seriously. Figures for water losses in canals, and the wide discrepancy between design assumptions and reality are given in Table 29. Data for field application efficiencies, and clarification on terminology used is given in Fig 12 and 13. Water distribution efficiency is defined as the efficiency of the canals or conduits in distributing the water from the conveyance network to the individual fields. In a world wide survey, efficiencies were found to range between 0.6 and 0.9.

Figure 12



The layout of an irrigation scheme (Bos and Nugteren 1974)

Figure 13



Average field application efficiencies for various irrigation methods as related to soil type (Bos and Nugteren 1974)

From: Oomen, 1990, 29 and 163.

Table 29. Transmission losses in canal irrigation in India.

Project	Canal System	Lined/ Unlined	Losses* Assumed	Measured
Dantiwada	Left Canal	U	10%	40%
(Gujarat)	Left Canal	L	2%	6%
Nagarjunasagar	Left Canal	U	8%	36%
(Andra Pradesh)	Left Canal	U	8%	21.2%
	Right Bank	n.a.	2-8%	16.7%
Mahanadi Canal System (Madhya Pradesh)		n.a.	2-8%	39.7%
Mula (Maharashtra)	Right Bank	n.a.	2-8%	24-25
Tawa (Madhya Pradesh)		n.a.	2-8%	22.9%
Chambal	Right Main	n.a.	2-8%	15%

* in cusec/msf - cubic feet per second per million square feet of wetted perimeter (except Dantiwada). The values 2-8% refer to Lined or Unlined canals in original source.

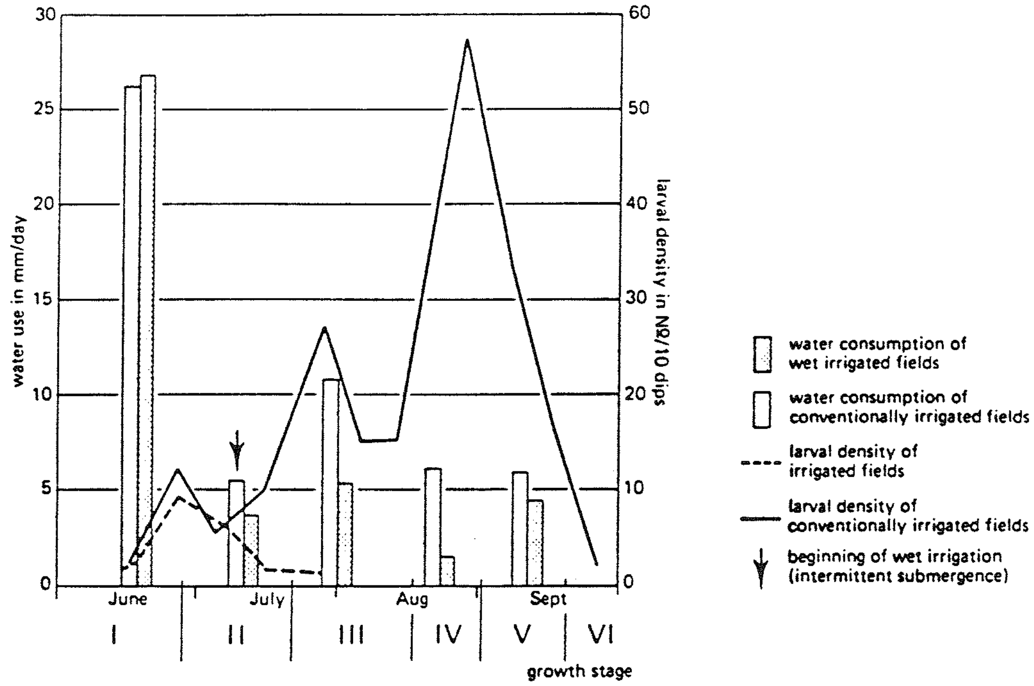
Source: R. Chambers, Managing Canal Irrigation. Practical Analysis from South Asia, 1988, p.114

In summary, all interventions in farm water management which help to promote a high irrigation efficiency also promotes vector control of diseases.

In rice fields, the number of malaria mosquito larvae and adults coincide precisely with irrigation activities, showing a single peak of mosquitos in single-cropped fields and two peaks in areas of double cropping. Where the main rice cultivation begins with the onset of the rains, all farmers tend to start preparing their lands. With water everywhere and a rice crop in various stages of growth, there are risks of crop diseases and opportunities for mosquitos to proliferate. These problems can be mitigated by dividing the area into blocks and observing cropping calendars staggered at intervals of two weeks, instead of one for the whole area. This will lower the overall peak demand for water, which in itself makes irrigation more manageable in rotational distribution systems, and it allows better vector control. Thus objectives of irrigation management for production and public health may be both served.

As noted before, serious mosquito problems had developed in China, and intermittent irrigation rather than chemical pesticides proved a more satisfactory solution. The results are illustrated in Fig. 14 and 15 (Oomen, 1990, 166).

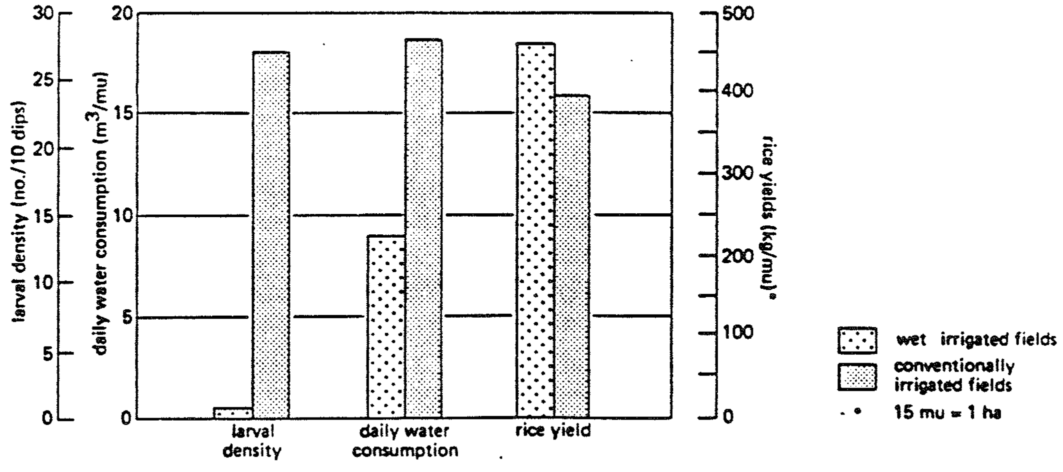
Figures 14-15. Effects of intermittent irrigation on larvae densities in China.



Comparison of the larval densities of *Anopheles sinensis* and *Culex tritaeniorhynchus* between fields of wet[1]) and conventional[2]) irrigation (after Ge Fengxiang et al. 1981)

[1]) 'Wet' irrigation: intermittent submergence with a thin water layer; when that layer has evaporated or evapotranspirated, a new layer is applied.

[2]) 'Conventional' irrigation: a permanent water layer of 5 to 15 cm is maintained.



Comparison of larval densities, yields, and water consumption in the fields of wet and conventional irrigation (after Ge Fengxiang et al. 1981)

Source: Oomen, 1990, 166.

Water efficiency would be improved by better methods of landscaping, grading and land levelling, but farmers often make a trade-off between own labour effort in land-levelling activities and using more water than required. As in many schemes farmers face uncertain water supplies for a variety of reasons, they try to get as much as they can when they can, rather then spend time in land-levelling in anticipation of uncertain flows. Head-enders often face abundant water and this is a strong incentive to substitute excess water to cover high lying areas as well for own effort in better land levelling. In contrast, tail-enders may have to devote considerable effort to obtain water, either within the tertiary unit in competition with neighbours, or in competition between tertiary units on the same canal. In addition, system design and system operation may not conform to design parameters, due to conflicts in dam operations, larger than expected conveyance losses, poor maintenance management by the irrigation bureaucracy and corruption in the allocation of waters (Wade, 1982).

Methods of irrigation are important in different ways. In general, systems use either continuous flows or rotational distributions of available flows. Because the stream size supplied to a farmer under rotational delivery is larger and the length of the canals simultaneously in operation is shorter, rotational delivery results in higher distribution efficiencies than continuous delivery. Rotational delivery also saves water, which might be used to expand the irrigated area. Under continuous delivery, more water will percolate from the canals to the subsoil, increasing the hazard of a rising water table, which may eventually create waterlogged areas within the irrigation scheme or dangerous pooling elsewhere.

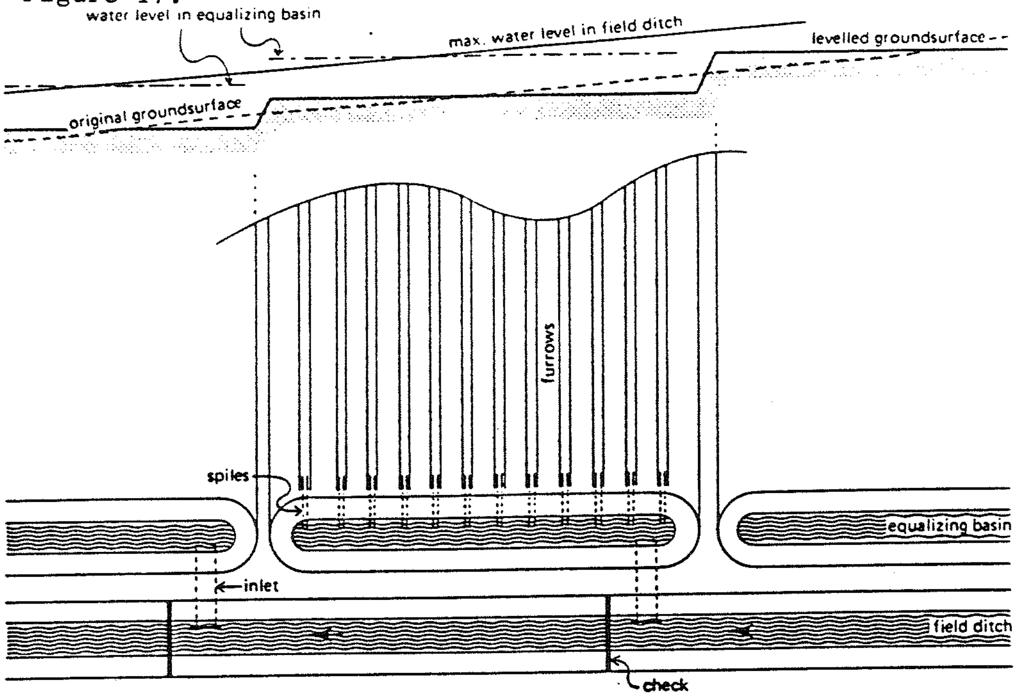
Rotational methods of delivery also have advantages for public health through vector control. Field canals that follow a cycle in which water is present for 2 weeks and absent for 2 weeks are unable to support snail populations. This is so, even if some snails are washed in from outside. Mosquitos require a different approach. Mortality in the larval stage is very high so a dry period of only a few days is sufficient to kill all the larvae.

Rotational irrigation has the disadvantage of involving higher investment costs, and may require the more frequent presence of the farmer, who may also have to irrigate at night. But the advantages far outweigh the disadvantages, so the conclusion is to recommend rotational delivery. In some countries, such as India, some southern states are attempting to change over from continuous flow to rotational delivery in old irrigation systems. Rotational delivery has been well established in Northwest India from the late 19th century (Malhotra, 1982).

Night irrigation is unpopular with farmers. Therefore, night-storage reservoirs are sometimes built, though it has negative effects in terms of vector proliferation. With siltation and aquatic weeds, such basins often become the sites of high densities of vectors. When night storage is strictly applied, and the basins are cleared in the day, the basins may dry out sufficiently to control vectors somewhat. But when nights storage also take on the function of general water storage for 'hoarding' in view of uncertainties in supplies forthcoming, the health risks of such reservoirs increase greatly. To illustrate some of these concepts lay outs for equalizing basins and night storage reservoirs are shown in Fig. 16 and 17 (Oomen, 1990, 172-3)

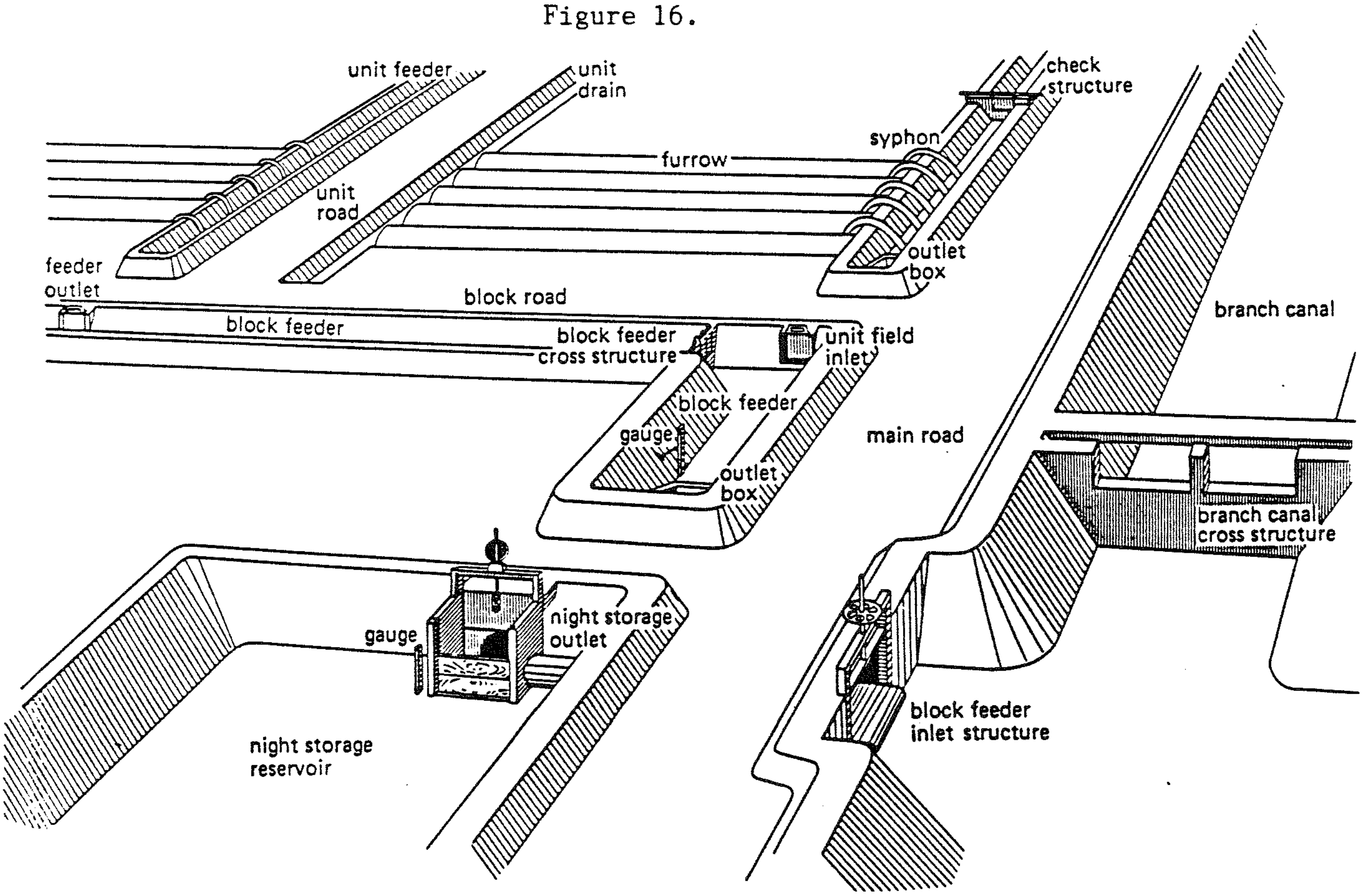
Other measures to control disease vectors are adequate ditch maintenance. Lining of field ditches often do not occur due to their cost. Considerations are identical to those for canal maintenance. The use of closed conduits for the distribution of irrigation water has a number of advantages over open ditches, though they are not widely used in developing countries. The advantages are the following: they are as effective as concrete-lined ditches in reducing seepage losses; they eliminate evaporation losses; they eliminate the need for weed control along the banks; the area that would otherwise be occupied by ditches can be sown to crops; pipe systems have lower operational and maintenance costs; by eliminating open water, they eliminate insect and snail breeding. Taking these factors into account, a more appropriate framework for cost-benefit calculations can be developed.

Figure 17.



Equalizing basins for levelled strips of land (after Roscher 1986)

Figure 16.



Layout of canals and structures, Bura Irrigation Project

Source: Oomen, 1990, 172-3.

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