ODA

Proceedings of the Conference on

Priorities for Water Resources Allocation and Management

Natural Resources and Engineering Advisers Conference

Southampton
July 1992

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Introduction

The first joint conference of ODA's Natural Resources and Engineering Advisers was held at the University of Southampton in July 1992. Besides Advisers from ODA headquarters there was representation from the ODA's Development Divisions, Aid Management Offices, Natural Resources Institute and also Associated Bodies. The conference was greatly enlivened by the presence of 18 non-ODA guest speakers and participants from a variety of academic institutions, NGOs and others involved in issues related to water in development.

The theme of the conference was 'water' and priorities for the allocation and management of the resource. ODA has been involved in water resource development since its inception but issues of allocation and management have become increasingly important. This has been reflected in increased international consultation on water as discussed below, and also in the need for greater linkage across the Divisions of ODA in water related issues. The 1991 ODA Natural Resources Advisers Conference discussed the theme of interdisciplinarity so that the bringing together of engineers, natural resources advisers and advisers of other disciplines as well as ODA administrators to discuss such a major cross-cutting theme was appropriate. The conference was part of the process of developing an integrated policy on water for ODA as already developed for other cross-cutting issues such as environment, gender, economic reform, management, poverty and good government.

The conference came at a time of increasing international concern with water related issues. In the World Bank's development report for 1992 clean water and adequate sanitation are put at the top of developing country priorities and a programme of action for more efficient management of water resources is recommended. The International Drinking Water Supply and Sanitation Decade (1981-1990) had been followed by the New Delhi statement which emphasised the urgent need to integrate water resources management whereby water supply, sanitation and irrigation were no longer treated as separate sectors. The Dublin Conference on 'Water and the Environment' in January 1992 stated the need for a further change in water resources development to a more holistic and multidisciplinary approach. International concern with water culminated in June 1992 at UNCED in Rio de Janeiro. Agenda 21, a major output of the conference, contains Chapter 18 entitled 'Protection of the Quality and Supply of Freshwater Resources: Application of Integrated Approaches to the Development, Management and Use of Water Resources'. Many of the presentations made in the ODA's conference in Southampton fall under the seven programme areas listed in Chapter 18: these include integrated water resources management, protection of aquatic ecosystems, water supply and sanitation and impact of climate change on water resources.

At a time of heightened awareness and increased interest in the requirements of developing countries for water resources, drought in parts of Africa continues to intensify and the problems of sharing the resources of international rivers such as the Zambezi, Nile, Jordan and Euphrates increase. Problems of drainage and salinity in major irrigation schemes escalate, irrigation increasingly competes with domestic water supply and hydro-power, and there is considerable interest in the consequences of possible climate change. The National Audit Office in its report on 'Overseas Aid: Water and the Environment' (May 1992) has made its recommendations following a review of 17 major ODA projects in the sector between 1977 and 1989. Donors, such as ODA, cannot necessarily increase the allocation of scarce cash resources to this sector (and statistics indicate that they are not doing so), but they can attempt to make their aid more effective by ensuring a more multi-disciplinary approach to project appraisal, design and implementation, and perhaps adopting new methods for co-ordinating the activities of the many entities involved in water management.

Against this background of international interest in water related issues the Conference's objectives were set. The aim was to create a baseline of common knowledge and expose ODA advisory groups to modern practices and current issues in water use and management. The conference also aimed to demonstrate a commitment to interdisciplinary working practices with the objective of maximising benefits from investment of aid in water use and management. The major objectives of the conference were to provide a framework of needs and opportunities in water resources allocation and management, develop a water resources strategy for action on priorities and establish an interdisciplinary working group.

The programme comprised eight sessions spread over two days in each of which two presentations were made followed by discussion. In this document the papers and a brief summary of discussions are given in the order of presentation, two each under the following headings:

- Priorities and conflicts in water resource development
- Issues in water resources management
- Domestic water use
- Urban and industrial water use
- Watershed management and land use
- Irrigation
- Aquatic resources
- The wider environment.

The full technical programme, summary of papers and working group conclusions are presented in a separate conference report. The results of working group deliberations which correspond with the above headings are summarised as key issues, main lessons and recommendations below.

Key issues

1. Water is an important renewable but scarce resource in much of the developing world and is increasingly a key constraint on development.

2. There is increased demand from rapidly growing urban populations and the priority between urban and rural, domestic and industrial and agricultural demand has to be addressed. The distinction between minimum water needs and demand should be made.

3. Water should be treated as an economic good and fully valued.

4. Institutions involved in water provision and delivery need reforming.

5. Participatory methods should be used both with farmers and domestic consumers in the allocation and development of water resources.

6. Water resource planning needs to be reviewed and the use of watersheds as a management unit needs to be considered.

7. There is generally a lack of reliable data on processes involved; more appropriate and accessible information is required.

8. An holistic, systems view of water resource management is needed using an interdisciplinary approach to understand the interactions.

9. The key issues are related to management, social and institutional structures rather than technical matters.

Main lessons

1. Strategies need to be developed for the allocation of water.

2. There is scope for increased efficiency of water use and more re-cycling of water for agricultural and urban use.

3. Operation and maintenance issues must be addressed in project design.

4. Research into opportunities for on-site sanitation is needed given its low water demands.

5. The distinction between use and consumption should be drawn.

6. A flexible approach is needed to cope with change and uncertainty in particular climatic change.

7. ODA needs to broaden its interdisciplinary thinking.

Recommendations

1. ODA should establish a multi-disciplinary working group to define the key areas of a water resources strategy.

2. The water resources strategy should help ODA to define its policy and determine priorities for future research and development activities.

3. Water centred thinking should be integrated into ODA through Country Review Papers and other mechanisms.

4. The strategy should consider whether to focus water related activities in a few key areas or countries.

5. On the basis of the strategy, systems-based research programmes should be established across ODA's administrative divisions with a common fund. Priorities to be addressed would be:

    - Further work to establish the full economic value of water and application of this to policy and projects wherever possible
    - Determination of minimum water requirements for urban areas
    - Research multiple uses and re-cycling of water
    - Irrigation systems
    - Coastal zone management
    - Common property resources.

PAPER 1

Demographic trends: implications for the use of water

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Summary: World population is growing at about 1.6% annually; even though the growth rate is falling, we can expect the total to rise from about 5.3 billion to over 8 billion in 2020. Virtually all of the increase will be located in the poorer countries, especially within the tropics, and furthermore most of the increase in the foreseeable future will be urban, not rural. Therefore, the management of water resources will become increasingly complex, especially in regions where precipitation is low, highly seasonal and/or very variable. To balance rural (agricultural) needs, urban needs and water requirements to maintain ecosystems will require the skills of the engineers and sensible water pricing policies, plus hard thought about the priorities for water use.

PRESSURES ON WATER SUPPLIES

Several trends are putting increasing pressure on water supplies: population and income growth, the trend to spatial concentration of people, the widening range of uses to which water is put, and the need to disperse and to transport waste products of all kinds. To begin to consider these matters, something must be said about the growth and the location of population, at present and for the foreseeable future.

Table 1 presents some recent estimates for the total world population and its distribution by broad geographical region. Most of the population increase will take place in the less developed regions, and especially in Africa, Asia and Latin America. Although these estimates are subject to error, it is highly unlikely that over the next 30 years or so the broad picture conveyed by Table 1 will be altered, unless some catastrophic and unforeseen event occurs. Thus, we can say with fair confidence that between 1990 and 2020, the less developed countries will gain about 2.7 billion people - a gain well in excess of 50% - all of whom will need water for the food they eat, for personal use, for the industries in which they work, etc.

TABLE 1
Estimated and projected population (milllions)

Geographical region	Year 1990	2000	2010	2020
World	5292	6261	7204	8092
More developed regions	1207	1264	1310	1342
Less developed regions	4086	4997	5895	6750
Africa	642	867	1148	1452
Latin America	448	538	629	716
North America	274	295	311	326
Asia	3113	3713	4240	4700
Europe	498	510	516	516
Oceania	265	301	336	368

Source: United Nations, 1991

The less developed countries are, practically by definition, relatively poor, as is shown in Table 2. If we compare Table 1 and Table 2, it is immediately clear that the bulk of future population growth in the less developed countries will be located in the low income nations which, in 1989, had an average GNP per head of only $ 330. If we assume, as is reasonable, that income per person will rise in these countries, at 1-2% per year it will take a long time for the absolute level of income to rise appreciably. At a growth rate of 2% annually, it would require 35 years for individual incomes to double.

TABLE 2
Population estimates and GNP per caput (actual and projected data)

Country group	Population 1990 (millions)	GNP per caput 1989 (£)	Average annual population growth 1990-2000 (%)
Low- and middle-income economies	4138	800	1.9
Low-income economies	3013	330	1.9
Middle-income economies	1125	2 040	1.9
Sub-Saharan Africa	496	340	3.2
East Asia	1580	540	1.4
South Asia	1156	320	1.9
Europe, Middle East, North Africa	440	2 180	2.0
Latin America, Caribbean	430	1 950	1.8
High-income economies	835	18 330	0.6
OECD members	776	19 090	0.5
Other economies	324	-	0.7
World	5298	3980	1.6

Source: World Bank, 1991

A very large proportion of the world's existing population, and the great bulk of the prospective increase, is located within the tropics and therefore in hot climates, which range from the semi-desert and desert conditions of the African Sahel to the extremely wet conditions of Bangladesh. But even where there is an overall abundance of water, even excess, seasonal drought is common. Furthermore, much of the tropical area of the globe is characterised by extremely heavy precipitation, with the implication that the control, and hence use, of water is much less tractable than is the case in the temperate climate of Western Europe.

Every bit as important is the rapid urbanisation that is going on in the less developed countries of the world. Table 3 provides estimates for past and future years of the proportion of the population residing in urban areas. This table shows that there is a long-standing urbanisation trend which is manifest in all the major world regions, and that the most rapid urbanisation is occurring in the less developed countries. Although these broad averages hide much diversity, the estimates available for 200 separate countries show that increases in urbanisation into the next century are to be expected in all but six countries - and all of these are already 100% urban (e.g. Bermuda, Cayman Islands and Singapore) (United Nations, 1991). So strong is the urbanisation trend that in the foreseeable future all of the increment in world population will live in towns. The United Nations (1991) estimates that the total rural population in the world will reach a peak in 2010 at 3.13 billion and will thereafter begin to decline slightly Table 4). This decline has been in evidence in the more developed regions since 1950; in the less developed regions, the absolute decline of rural population will occur after 2015. By major

TABLE 3
Percentage of population residing in urban areas

Geographical region	Year 1950	1960	1970	1980	1990	2000	2010	2020
World	29	34	37	40	45	51	57	62
More developed regions	54	61	67	70	73	75	78	81
Less developed regions	17	22	25	29	37	45	52	58
Africa	15	18	23	28	34	41	47	54
Latin America	42	49	57	65	72	76	80	83
North America	64	70	74	74	75	77	80	83
Asia	16	22	23	26	34	43	50	56
Europe	57	61	67	70	73	77	80	83
Oceania	61	66	71	71	71	71	73	76

Source: United Nations, 1991

TABLE 4
Rural population (millions)

Geographical region	Year 1990	2000	2010	2020
World	2902	3063	3130	3076
More developed regions	3311	3179	2895	2534
Less developed regions	2571	2745	2841	2823
Africa	425	514	604	669
Latin America	128	127	126	123
North America	68	67	61	53
Asia	2042	2127	2132	2051
Europe	133	119	103	87
Oceania	8	9	9	9

Source: United Nations, 1991

geographical area, it is only in Africa that the rural population will continue to rise in absolute terms throughout the period to 2020; even in Asia, the peak will be reached in 2005 and thereafter the absolute number of rural dwellers in that region will decline.

URBAN GROWTH

One of the striking features of urban growth in the less developed countries is the emergence of very large cities - usually known as mega-cities. If we take a threshold of eight million for an agglomeration that can be called a mega-city, then in 1950 there were just two - London and New York. The number in the more developed regions of the world increased to six by 1990 and is expected to remain at that number until 2000. In contrast, by 1990 there were 14 in the less developed countries, and that number is expected to rise to 22 just 10 years later (United Nations, 1991). Table 5 gives details of the growth expected for those 20 cities which in 1990 had already reached eight million, from which several points quickly emerge. First, the very biggest cities are already huge, at something like 20 million, or just under two-fifths of the United Kingdom population and nearly three times the inhabitants of London. Second, the

TABLE 5
Urban agglomerations with 8 million inhabitants or more in 1990

City	Population (millions) 1990	2000
Mexico City	20.2	25.6
Tokyo	18.1	19.0
Sao Paulo	17.4	22.1
New York	16.2	16.8
Shanghai	13.4	17.0
Los Angeles	11.9	13.9
Calcutta	11.8	15.7
Buenos Aires	11.5	12.9
Bombay	11.2	15.4
Seoul	11.0	12.7
Beijing	10.8	14.0
Rio de Janeiro	10.7	12.5
Tianjin	9.4	12.7
Jakarta	9.3	13.7
Cairo	9.0	11.8
Moscow	8.8	9.0
Delhi	8.8	13.2
Osaka	8.5	8.6
Paris	8.5	8.6
Manila	8.5	11.8

Source: United Nations (1991)

fastest growth will be in the less developed countries, and very rapid it will be. In addition, other cities, all in the less developed regions, are rapidly heading for mega-city status - Dhaka, Lagos and Bangkok, for example.

The poverty of many of the developing countries is reflected in the large scale of squatter, or illegal, settlement which characterises much of the explosive urbanisation in Africa, Asia and Latin America. This phenomenon has been documented elsewhere (Chisholm, 1992). The point of main relevance here is the enormity of the task which is faced merely to provide the most basic systems for delivering potable water and removing wastes; such provision is essential if minimum standards of private and public hygiene are to be achieved, standards which are essential if the health of the population is to be improved.

PRIORITIES FOR WATER USE

The key fact with which policy-makers will have to wrestle is the need to assess priorities for water use as between rural and urban needs. Some indication of the problems faced can be inferred from Table 6. At first sight, if only 15% or less of the available water is being used there is plenty of scope to expand supplies by suitable engineering works. However, supplies are unequally distributed both in space and time, so that it will never be possible to exploit the full potential. We know, also, that in substantial parts of Europe and North America in particular, demand already exceeds available supplies, while in some of the oil-rich states of the Middle East water usage actually exceeds local supplies - Qatar, Saudi Arabia and the United Arab Emirates for example - the difference being made up by desalination plants. Table 7 lists all the countries in the world in which water usage already equals or exceeds 20% of available supplies. While it is true that the greatest pressure is being felt in dry countries, it is notable that several important developed countries are included. Furthermore, if consumption were to double in the next few decades in countries such as India and China, their consumption of water would rise to well in excess of 30% of available supplies.

TABLE 6
The use of the world's freshwater in the 1980s: broad geographical regions

Geographical region	Annual withdrawals: Cubic metres per caput	Annual withdrawals: As % of 'available' water*	Percentage distribution of water use: Domestic	Industry	Agri-culture
World	660	8	8	23	69
Africa	244	3	7	5	88
North and Central America	1692	10	9	42	49
South America	476	1	18	23	59
Asia	526	15	6	8	86
Europe	726	15	13	54	33
USSR	1330	8	6	29	65
Oceania	907	1	64	2	34

NB Estimates refer to various dates in the 1980s
* Available water includes internal renewable water and river flows from other countries
Source: World Resources Institute and United Nations Development Programme, 1992

TABLE 7
The use of freshwater in the 1980s: selected countries

Country	Annual withdrawal as % 'available'	Country	Annual withdrawal as % 'available'
Cape Verde	20	Spain	41
Japan	20	Iraq	43
North Korea	21	Barbados	51
France	22	Afghanistan	52
Cuba	23	Tunisia	53
United Kingdom	24	Cyprus	60
Oman	24	Belgium	72
West Germany	26	Israel	88
East Germany	27	Malta	92
Italy	30	Egypt	97
Poland	30	Yemen (Peoples Democratic Republic)	129
Singapore	32	Yemen (Arab Republic)	147
Pakistan	33	Saudi Arabia	164
Morocco	37	United Arab Emirate	299
Iran	39	Libya	404
Madagascar	41	Qatar	663
Jordan	41		

Source and notes: See Table 6

These aggregate consumption figures pay no attention to several factors of importance. First, they ignore medium- to long-term changes in precipitation which are attributable to natural oscillations in world weather systems and man-induced climatic change. Second, the main growth in demand will be geographically concentrated in urban areas, which implies major engineering works to gather and transport water, and then to cope with the resulting wastewater which, by virtue of its geographical concentration, should not be released back into rivers, lakes or the oceans without proper treatment. In Europe, 72% of sewage is treated in some degree, in the Mediterranean it is only 30%, in the Caribbean under 10%, and in the following regions the percentage is almost zero - Southeast Asia, South Asia, South Pacific, and West and Central Africa. The growth of the urban population will exacerbate this problem (World Resources Institute and United Nations Development Programme, 1992; for further details, see United Nations, 1989).

In addition, however, water plays a vital part in the maintenance of ecosystems and it is quite clear that were anything approaching the total 'available' water to be used, there would be serious and potentially devastating consequences in many situations. The ecosystems of rivers and their associated wetlands, estuaries and deltas are vital for many forms of wildlife and in addition provide important sources of gainful employment. It cannot possibly be assumed that all the water which ultimately 'escapes' to the sea in this manner is 'wasted' and should be otherwise used. It is a matter for investigation and judgement as to how much water must be retained in the natural ecosystems to ensure their maintenance. My own belief is that, too often, these limits have been exceeded with scant regard for the long-term consequences. One aspect of ecosystems that is often overlooked is the fact that, in addition to water, rivers carry dissolved minerals and sediments. Estimation of the latter is subject to very wide margins of error (Douglas, 1990; cf. World Resources Institute and United Nations Development programme, 1992). Douglas gives estimates for 26 rivers which together transport about 5.2 billion tonnes of sediment each year, an average of just over 200 million tonnes per river. Globally, the mean annual discharge of river sediment to the sea has been variously estimated between 13.5 billion tonnes and 24.0 billion tonnes. All of this is sediment which has entered the river systems and which, if not discharged to sea, will accumulate along the length of the river in one of two ways: by filling reservoirs; or by aggrading the course of the river and so building the river above the areas over which it flows until its banks cannot contain a major peak discharge. Meantime, in estuaries and delta areas, the absence of sediment input may lead to serious erosion, as in the case of the Nile delta (the problems being compounded by the penetration of saline water into the groundwater).

RENEWABLE WATER RESOURCES

If we remember the considerable error of estimation involved, the volume of annually renewable water may be compared with the volume which is discharged to the sea by rivers (Table 8). The river discharges have been obtained by summing the totals for the individual rivers for which data are reported; although these include most of the major rivers, the aggregates so obtained

TABLE 8
Renewable water resources (in cubic kilometres)

Region	Annual renewable water resources	Discharge of main rivers[1]
Africa	4 184.0	1 722.0
North and Central America	6 945.0	2 011.0
South America	10 377.0	7 701.9
Asia	10 485.0	1 934.2
Europe	2 321.0	302.1
USSR	4 384.0	2 045.0
Oceania	2 011.0	99.0
World	40 673.0	15 815.2

[1] Sum of discharge at the mouth for rivers for which data recorded: figures are, therefore, minima

Source: World Resources Institute and United Nations Development Programme, (1992) represent minimum estimates. In a rough-and-ready way, we may say that the larger the river discharge is relative to total water availability, the greater is the scope for further river abstractions without seriously impeding the transport of sediment.

Aggregate figures of the kind mentioned above do not give guidance as to what it is feasible to do in particular situations, but they do suggest that great care must be taken in the exploitation of water resources. However, they do show that the greatest pressures are likely to arise in supplying urban populations, on account of their growth, geographical concentration and the problem of dealing with effluents. Water will of course be needed to raise the crops to feed the urban dwellers, but the growth in demand for water will almost certainly be greatest in the urban areas. It will be essential to ensure that the short- and medium-term urban needs for water do not result in projects which are unsustainable in the long run and damage rural environments irretrievably.

CONCLUSIONS

Consequently, urgent thought must be given to the following issues:

- Ensuring that water is not used extravagantly.
- Ensuring that polluted waters are not returned to hydrological systems to carry infections and harmful pollutants to downstream populations.
- Seeking to re-cycle as much water as possible.
- Giving consideration to the uses to which water is put. Water-borne sewerage may be a luxury that cannot be afforded, and other means may have to be found to dispose of excreta safely.

These conclusions are broadly consistent with the view of the World Bank (1992) that the major problems of water supply relate to health and hygiene rather than increased agricultural usage. Therefore, given the demographic trends outlined, urban problems are going to gain in prominence, as is the need for the proper pricing of water as an increasingly scarce resource.

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DISCUSSION

The discussion opened with consideration of whether it was feasible or desirable to resist increasing urbanisation. It was concluded that, in spite of some attempts to stem the flow from country to town, this trend would have to be accepted as a basis for planning. On the question of the returns to the use of water in different sectors, it was pointed out that there are gross distortions adopted in the pricing of water supplied by publicly owned institutions, and in the pricing of the crops grown under irrigation. This is true in the developed world as much as in the developing world.

It was concluded that only by more efficient use of water and reallocation between sectors could future needs be met. This would be assisted by realistic pricing and would require a radical change in the conventional wisdom on appropriate technology e.g. the use of non water-borne sanitation for large cities.

PAPER 2

Fortunately there are substitutes for water: otherwise our hydropolitical futures would be impossible

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Summary: Evident mismatches exist between the demand and supply of water in many countries particularly in the semi-arid and arid worlds. The resulting food gaps which concern both the national governments of these countries as well as the international agencies which extend assistance to them, appear at first sight to pose challenges beyond the economic and political capacity of peoples and institutions to make the necessary adjustments. The institutions with responsibility for the allocation and planning of water use at international, national and local levels do not seem to be robust enough, or informed enough, to provide the necessary leadership to ensure that scarce water is used sustainably.

It will be argued that despite the great difficulties which governments and users face in coping with the need to manage water so that it brings a sound return, as well as according to principles of equity, safety, and ecological sustainability, everywhere there are examples of conflict over water being avoided. And while the avoidance of conflict can in many cases be calculated to have been at a cost to the environment, nevertheless, to date conflict of a hot nature has been avoided. Case studies from a region seen to have the worst water resource future outside the industrialised world, the Middle East and North Africa, will be discussed to exemplify the numerous strategies adopted by countries in their various ecological, economic and political circumstances. A fortunate few governments have substituted oil capital for water while others have filled the food gap, which is generally an expression of the water gap, by ceding economic and political autonomy.

INTRODUCTION

It is becoming increasingly clear that some regions of the world have entered a phase of severe water shortages where food imports are rising rapidly and indigenous agricultural sectors will never be able to produce sufficient food to fill the burgeoning food gaps. The most serious food shortages preoccupying national governments and those which have gained the attention of the international community are the shortages in the semi-arid countries of the Middle East and Africa where food imports have been rising at rates of over 10% per year in some countries. The reason that the shortages have gained the attention of the international community is that some of the largest of them have occurred in poor African countries without the capacity to purchase food on the world market and in some cases to distribute it once obtained via international assistance. Food deficiencies are regarded as uncomfortable yet most of the major civilisations of the past 3000 years have prospered on the basis of 'international' food markets, and it should be noted that regional food trade certainly preceded the establishment of the 'nation state' by at least two and a half millennia, as well as the international agencies, the NGOs and overseas development assistance. The pre-eminence of the temperate world in the food trade is also a recent phenomenon. In the ancient world dominated during one of its phases by Rome it was the semi-arid regions of northern Africa and especially the Nile delta which provided the grain for the metropolitan and other urban populations further north. Such was the agricultural productive capacity of these regions in relation to contemporary populations that they were able for many centuries to export surplus grain and olive oil.

Trade has been the normal remedy for economic entities facing food shortages. In the past, and especially in the nineteenth century, the terms of trade were often strongly affected by colonial relationships and therefore exposure to the strategic food insecurity by Britain, for example, was underwritten by military and naval dominance. It could be argued that the food deficits of the developing countries of the late twentieth century are of a different type in that these countries have no military strength, and only the oil-rich have the economic strength with which to ameliorate the discomfort of food deficits. But there are at the same time numerous examples of substantial industrial economies being dependent on food imports via unfettered trading relationships. Britain's later years of empire and industrial leadership were based on flows of food via normal trade with the United States, with southern South America and fairly straightforward trade with Australasia. The industrial giant of the late twentieth century, Japan, has a large food deficit. Nor are food shortages a problem for the oil economies of the late twentieth century which are in all other ways significantly deficit economies. These economies can gain access to food on the world market. The existence of a food deficit is clearly only a problem for a poor country. Any problems which Japan has in the area of food are to do with the economic leverage it exerts to protect its own producers which in turn anger the potential importers of food and are nothing to do with its actual capacity to purchase imports of food. Nor for the foreseeable future will food shortages be a problem for an economy with either the capacity to generate foreign exchange, or the ability to earn the political patronage of a power with the will to make foreign exchange available to the poor food deficit economy for the purchase of food. Egypt is such a case.

FOOD GAPS AND WATER GAPS: WATER AND THE AGRICULTURAL SECTOR

Why is the issue of food such an important one? It is because the production of food requires between one-half metre depth and one-and-a-half metres depth of water to produce a crop in one season, and in those regions where two or more crops can be produced ,then between one and three metres depth of water are needed annually. No other activity which extends over large areas uses, or disposes of, as much depth of water per unit area as agriculture with the possible exception of the storage of water in massive structures on the river systems of arid and semi-arid regions such as those in the south west of the United States, the Middle East and Africa and in South Asia. But even they are small in area compared with the areas actually irrigated - compare for example the *c.* 300 000 ha surface area of Lake Nasser/Nubia with the *c.* 2 900 000 irrigated hectares in Egypt. The losses by evaporation at the Lake actually exceed 20% of the water allocated by Egypt to the production of crops and amount to almost twice the volume of water used by non-agricultural sectors - industrial and municipal use - in Egypt but they are still modest in comparison with the volume used annually in agriculture.

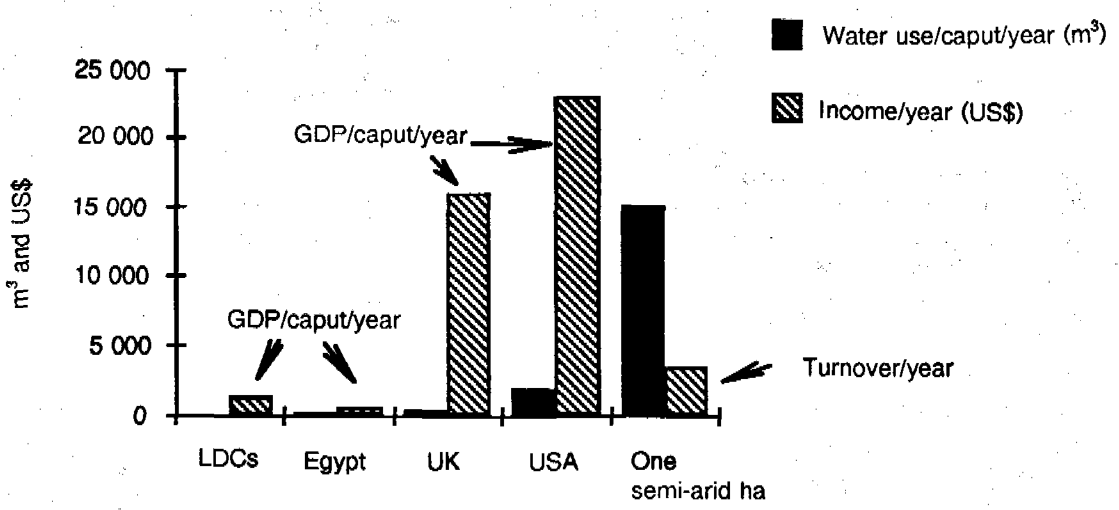
No other economic activity uses as much water per unit of area as agricultural applications. No other activity, economic or social, generates as little per cubic metre of water as does agriculture with the obvious exception of water allocated to enhance social and environmental amenity where there are problems of determining the economic value of such amenity returns. In other words, economic returns to agriculture are relatively poor compared with those from industrial activity or from municipal uses even if the achievement of amenity is assigned even a modest value. It is interesting to compare the use of water on a hectare of irrigated land with that by domestic water users in different economic circumstances throughout the world (see Table 1 and Figure 1).

In all countries or parts of countries where irrigated agriculture has been embarked upon, whether 5000 years ago or just in the past half century, then the proportion of water which has to be allocated to irrigated agriculture exceeds 70% of the total water use and in many cases it exceeds 90% of the national water use budget. With such high proportions of water allocated to a sector which brings relatively poor economic returns, although it must be emphasised that the social returns are significant if difficult to quantify, the impact of such allocations on national economies is major. Unfortunately decisions to irrigate and produce food are made on the basis of addressing a perceived national security imperative - food security, and not as just one more adjustment that has to be made to optimise the management of a national economy where there are unavoidable associated constraints such as scarcity of water.

TABLE 1
The use of water in different countries by individual domestic users compared with that on one hectare of irrigated land in a semi-arid country and comparing earning capacity - 1991 estimates (per caput)

	Developing countries	Egypt	UK	USA	One hectare in irrigated agriculture
Water use/ year (m³)	<100	100	500	2 000	15 000
GDP/year (US$)	1 500	700	16 000	23 000	1 500-5 000

FIGURE 1
Water use and returns to water in various countries to illustrate the heavy water use in agriculture



Source: World Bank and author's estimates
Notes: It is assumed that the semi-arid hectare is irrigated in 2 seasons
The numbers supported by an irrigated semi-arid hectare will vary with the economic environment: in an LDC an irrigated hectare can support 1 or more families; in the industrialised world it can require between 5 and 10 irrigated hectares to support a family

The statistical background to the food security problem is a stark and worrying one in most semi-arid countries and regions, especially as governments tend to assume that closing the food gap should be achieved through the development of indigenous natural resources. The food imports of a group of countries which have encountered serious water resource problems, those of the Middle East and North Africa (Khaldi, 1984), are rising rapidly and are a powerful illustration of the increasing scale and prevalence of water resource problems. The economies of the countries of the Middle East are not uniform, however, in terms of natural endowment; some are oil rich while others are not; some have large populations with a propensity to consume large volumes of food and generate large food import demands while others do not; and some have the renewable natural resource base to develop their agricultural sectors significantly while most do not. Table 2 suggests a typology of national economies for the region characterised by the underlying strength of the economy, the propensity to import food, the capacity to export food and the status of their water resource gaps.

TABLE 2
A classification of the countries of the Middle East and North Africa with respect to water availability and pattern of trade

Country	Balance of trade ($bn)	Food trade ($bn)	Water deficit (1) (km^3)
Countries with strong trading positions, being major food importers and where the *water deficit is not significant* - for them the international political economy is not affected by water			
Middle East			
Bahrain	-0.1	-0.25	-0.15
Iran	+2.0	-2.00	-0.00
Iraq (pre Aug 1990)	+5.0	-2.00	-0.00
Kuwait	+3.0	-0.30	-0.15
Qatar	+1.0	-0.15	-0.10
Saudi Arabia	+4.0	-3.50	-1.00
UAE	+7.0	-0.90	-0.20
North Africa			
Algeria	+0.2	-2.00	?
Libya	+4.0	-1.10	0.30
Countries with weak trading positions, being major food importers and where the *water deficit is significant or very significant* (Jordan) - for them the international political economy could be seriously affected by water			
Middle East			
Israel	-1.4	-0.30	-0.20
Jordan	-2.0	-0.30	-0.10
Lebanon	-1.5	-0.20	0.00
Syria	-2.0	-0.50	-0.15
Yemens	-1.0	-0.10	
North Africa			
Egypt	-6.0	-5.50	-10.00
Morocco	-1.0	0.00	potential deficit
Tunisia	-1.0	-0.20	-0.20
Countries with weak trading positions, but being food exporters and where the *water supply should ensure future food self-sufficiency* (provided Sudan can escape internal political disruption) - for them the international political economy is not affected by water			
Middle East			
Turkey	-5.0	+1.50	+10.00
North Africa			
The Sudan (2)	-0.5	+0.10	+4.00

Source: UN and World Bank data and author's estimates

Notes:

(1) The notion of deficit is difficult to define in that it depends on current national policy with respect to water allocation. In Egypt, where increased food output is a stated policy, it is possible to estimate the amount of water needed to meet the national goals. In countries like Jordan and Israel, where adjustments are being made to reduce water use in agriculture, the concept of a deficit is more difficult to define. Quantifying the deficit is less important than recognising the relevance of the deficits to the agricultural future of the region.

(2) The Sudan's position is so affected by the current internal problems that the renewable resource potential of the country cannot be realised. It is therefore difficult to categorise.

Table 2 demonstrates that only Turkey and the Sudan have futures which include, for a period at least, self-sufficiency in food. The others all endure significant food deficits and these deficits are rising. The measures taken by the government of Saudi Arabia to develop groundwater to produce food including food staples such as wheat have been remarkable, in that it is estimated that the agricultural sector contributed 8% of the Saudi GDP in 1990, an extraordinarily high level in an oil-enriched economy. But these policies are neither economically nor ecologically sustainable. Water withdrawals are far beyond natural recharge and the capacity to subsidise the use of irrigation water even for an economy such as that of oil-rich Saudi Arabia has to be questioned in the light of the military events in the Gulf in 1990 and 1991 when it was revealed that not only was Saudi Arabia's economic stability dependent on the will of the Western industrialised community, but territorial security was also dependent on the whim of the military will of the same industrialised countries. Chasing the fantasy of food self-sufficiency (Allan, 1983) by Saudi Arabia is as irrelevant as pretending that it can be militarily secure. Misallocating funds to the achievement of either the agricultural or the military fantasy actually weakens the economic position of Saudi Arabia while strengthening the economies of the industrialised countries which supply agricultural equipment and infrastructures on the one hand and military equipment and defence infrastructures on the other.

The most interesting feature of Table 2 is the extent of the estimated water deficits in the national economies of the Middle East and North Africa. All of these deficits are rising with the increased demand for water both from agriculture and the other sectors of the respective economies. Yet no country has renounced food self-sufficiency as a major feature of national policy except very briefly, Israel, in the first half of 1991. But this glimpse of the direction which all governments of the region will ultimately have to embrace was very brief indeed as the posture was uncomfortable for Israel internationally and policy making on water as well as in all areas was overtaken by the unexpected acceleration of the Peace Talks at which it was not possible for Israel to indicate that it could cut water consumption. The heavy rains of the winter of 1991/92 also had their political influence in that they enabled those managing national and local water to relax as they watched water storages, such as Lake Tiberias/Kinneret rise and the coastal aquifers recover. These had been at crisis level during the preceding three years of severe drought.

The historical, psychological and political backgrounds to the development of food policy and related water allocation are very important. Governments of almost all countries find that there is a natural political alliance between apparently responsible leaders and officials on the one hand and the rural community which produces food on the other. The former want to ensure national security including basic food needs. The rural community is the major element in the economy enabling food production and also therefore the major enabling element in the achievement of a country's potential security with respect to food. The natural alliance between those responsible for food security and those capable of providing it dominates policy making in the variously endowed economies of the water scarce Middle East. It also dominates policy making in most economies throughout the world not least in the EC with profound and distorting consequences for world trade in food and for the tormenting discussions in the GATT conferences. But the EC and the Middle East, while resembling each other in terms of area and the size of population, are very different with respect to water resource endowment and economic competence. In the EC water is rarely a constraint while it is a constraint in all countries except Turkey, the Sudan and the Lebanon in the Middle East. Yet in both the Middle

East and the EC countries, despite their differing water resource endowments, water in the agricultural sector is regarded as virtually a free good and in many parts of the Middle East as a real free good. The dangerous fallacy underlying agricultural and especially food production policies of the countries of the Middle East is that water is free. This assumption lethally distorts the expectations of the farming community and also prevents officials at all levels from making rational judgments concerning the allocation and use of water as the real costs of water are not evaluated in the sectors that use water. If the real costs of water were taken into account, preferably in procedures of environmental accounting where the future costs of current policies would also be counted, then water would be allocated to uses more beneficial to the economy as a whole in the long term. At present, users of water have no incentive to use water efficiently and governments have no incentive to realise efficient returns to water as there are no institutions or mechanisms which effectively enable its value to be recognised in transactions of distribution and use by either individuals or by the state.

Any discussion of food production should also include reference to the fact that food is just one agricultural commodity. Agricultural and food production can be examined at the sub-sectoral level and disaggregated and evaluated in terms of returns to investment, to labour, to land - or most relevantly as far as we are concerned here - returns to water. Major agricultural economies in the Middle East have for the past century or more emphasised non-food crops such as cotton, and in the past four or five decades have progressively turned from the production of staple foods to the production of high-value food crops both for the domestic market as well as for export. This last trend is consistent with the principle of maximising returns to water and could be seen as a rational approach to resource management. But it could be argued that such practices have come into effect not so much because of rational national policy but as the result of special international circumstances in at least one of the major agricultural economies of the region, Egypt. Here, the US self-imposed obligation to reduce tension between Israel and Egypt involved the stabilisation of the economies of both countries with massive annual subsidies and in the case of Egypt the provision of food aid. The shift to high-value crops has been stimulated not so much by a wish to gain better returns to water as by the externality of free, or at least very cheap, food staples. The heavily subsidised food staples on the world market exist through the competing down of the world price for such staples by the EC and the USDA.

WATER ALLOCATION AND THE POLITICAL ECONOMY OF WATER

All economies are political economies but, as there are no concepts of political science which can be readily operationalised into numbers and statistical indicators, the political dimension of such matters as water allocation and management are not readily described still less used in analysing the shape of international and national economies. Unfortunately it is economic indicators which are used exclusively in monitoring and evaluating the performance of political economies despite the fact that it is political processes which determine their shape and the directions in which they develop. If evidence is needed of the significance of political ideology we need look no further than the UK water industry which has recently been reorganised to accord with a particular view on what is an efficient institutional regime. Meanwhile in the region used mainly to illustrate the arguments in this analysis, the Middle East, political inspiration and pressures, internal and external, determine for example the water allocation policy within the Israeli economy. At the same time the lobbying of the Jewish/Israeli lobby in Washington has ensured a flow of financial resources from the United States which has protected the Israeli economy in general and its agricultural sector in particular from the market forces which would have stifled the extremely imaginative, but non-viable, Israeli agricultural initiatives, especially those in the south of the country. In Libya, politically driven policies to utilise remote water on false economic assumptions concerning its viable use in agriculture have set the direction of water provision policies in the 1980s and continue dangerously to inspire those of the 1990s. Meanwhile Egypt's water resources are being allocated and developed according to political relationships which lead to unsound economic assumptions which in turn lead to unsound economic outcomes and the misallocation and mismanagement of scarce water.

Water misallocation and mismanagement in an economic sense occurs when the following policy goals are ignored. These goals are relevant at all levels - at the international (river basin), national (sectoral) and local levels:

- *Secure and co-operative use:* Water-using interests must come together in a political and social context which will facilitate optimum resource use in order to promote co-operation in water use at all levels.

- *Economic and sustainable use:* Scarce water must be allocated and managed so that it brings an optimum economic return now and in the future according to sustainable economic principles.

- *Socially beneficial use:* Water should be allocated and managed at all levels so that social benefits from its use are optimised - that is the social benefits of existing water allocation should be recognised and the social costs of reallocating water should also be recognised.

- *Safe water should be provided and wastewater safely processed and where possible re-used.*

- *Environmentally beneficial use:* Water should be allocated and managed according to *ecologically sustainable principles.*

  Note: 'optimum' and 'optimised' are used to indicate optimisation in terms of the overall good of the relevant population or political entity. At the international level this will apply to the river basin or groundwater domain, at the national level it will apply to inter-sectoral allocation and management and at the local level it will apply to intra-sectoral/utility/authority/firm allocation and management of water within the province, municipality etc. The trade-offs are disagreeably numerous.

It will be noted that the first goal is a political one recognising the primacy of the political context for the development and implementation of economically and ecologically sustainable policies. Only through effective political institutions will leaders have the confidence to direct the implementation of measures affecting water resource allocation and management at the sector level at home, or at the international level reach acceptable international agreements. The other goals are unexceptionable and are familiar recommendations in the multi-objective programmes of the international agencies. That the principles on which these goals are founded are rarely comprehensively addressed by water managing institutions and could not possibly be the basis of the existing national policies of the leaderships and departments of government of any current Middle Eastern government substantially explain the negative economic and ecological outcomes of current water management in the region.

National allocation

The hydropolitics of water at the sectoral level within individual countries in the Middle East are based on the false notion that food self-sufficiency is an achievable objective. The attainment of food self-sufficiency is clearly an attractive and legitimising goal and therefore a dominant one at a national level and also a goal judged to be very appropriate within the agricultural sector. Unfortunately it is so legitimate that once adopted its attainment appears to sanction all decisions even if they may lead to outcomes that contradict goals other than that of production. Goals such as the attainment of economic productivity and sustainability, as well as the provision of sufficient safe water, the equity of access and the achievement of ecologically sound and sustainable allocation and management are rarely consistent with the simple increase of irrigated area and the increased use of water.

Despite the primacy of the self-sufficiency goal it has not anywhere been achieved, with the exception of Turkey in most years. The economies of the countries with high food needs as a consequence of large populations, such as Egypt, have become major food importers. And these Egyptian food imports represent a water gap of at least 10 km^3 water per year, approaching 30%

of annual agricultural water consumption. Countries with small populations have equivalent food and water gaps, for example Jordan - see Table 2.

The water deficits do not, however, necessarily lead to international conflict and those scientists and commentators who for the past two decades or so have been advocating the dangers of resource scarcity with respect to the future economic stability of, and international conflict between, the countries of the region (Clarke, 1991; Naff and Matson, 1984; Starr and Stoll, 1987) have to explain why there has been no unresolved international conflict over water in the years since 1967 which was the last occasion when water could have been an underlying element in the war of that year between Israel and its Arab neighbours. Egypt has moved into a hopeless water deficit through its own internal demographically driven demands for food; Jordan has also faced damaging water shortages in both it agricultural and its municipal supply systems during the past two decades and there is no immediate indigenous economic remedy on the supply side. The same is true to a lesser extent of Syria which has, however, the additional complication of uncertainty over the future flow of the Euphrates (Kolars and Mitchell, 1991). Iraq has temporary problems stemming from the consequences of two economically crippling wars which have left it unable to deploy its oil wealth to subordinate its relatively unimportant water constraint. Iraq will be rich again and will not be constrained by intrinsic water scarcities and other natural resource deficiencies and it will resume its pattern of importing food to meet its requirements just as it did increasingly throughout the 1970s and the 1980s. The oil-rich states of the Arabian peninsula are seriously aggravating their water resource futures by extraordinary investments in agricultural production in, for example, Saudi Arabia where wheat exports have been possible since the late 1980s and the agricultural sector was calculated to have contributed 8% to Saudi GNP in 1990. In Abu Dhabi the use of water for the enrichment of the visual environment was carried beyond Californian and even Phoenix, Arizona standards. The Saudi experience would appear to mark the extreme of what an economy is prepared to devote to the achievement of the indigenous production of food staples such as wheat (note soft wheat and not hard wheat) in circumstances of unlimited supplies of capital. The answer seems to be about four to six times the world price of wheat. In Abu Dhabi there seems to be another version of extreme commitment to a single goal: in this case to the attainment of exceptional water resourced visual amenity. Here it would appear that, again, in circumstances of unlimited supplies of capital, it is possible to devote most of the national water budget to a particular purpose reflecting allocations of over one % of the national GNP to this single aspect of environmental amenity.

Yemen has very different problems. With a population of 11.6 million in 1990, deficient and difficult to manage water resources, and as yet very little oil, its recent economic past has been dominated by flows of remittances from Saudi Arabia. Its political system is very fragmented with the autonomy of tribal leaders strong. In these circumstances the chances of closing the increasing food gap through the improvement of the allocation and management of water is remote.

North African countries also have poorly matched water resource demands and supplies. Morocco has modest renewable water resources; the other countries have serious water deficits to which they are adjusting with varying strategies. Libya is developing its fossil groundwater to replace the over-used coastal aquifers by constructing pipelines from the southern fossil water resources by constructing pipelines to the coast.

All the countries of the region have continued to attempt to sustain or expand the allocation of water to agriculture. This strategy is not rational according to any economic or ecological criteria. And the reason it is pursued is because those in leadership positions have no incentive to apply economic principles consistent with sustainable production. The officials allocating, and the farmers managing, the water also have no pressures on them to use the water economically because they currently receive it as a free resource, and further there is no market related or effective socially driven discipline in water management in the oil rich countries and imperfect disciplines in the rest. The position vis-à-vis water allocation and use arises because neither national leaders and policy makers, nor the agricultural users, have any incentive to defer the immediate political benefits on the one hand, and the economic ones on the other, which the respective parties are deriving from current practice.

River basin allocation

Possibly the most important issues of water allocation in terms of regional tension over water is at the international level. Rising demands for water within international river basins match neither the volumes available naturally, nor those allocated by international agreements which have been put in place during the 20th century. The only agreement which has some significance is the 1959 Nile Waters Agreement between Egypt and the Sudan. This allocated 75% of current estimated long-term flow to Egypt and 25% to the Sudan with 'new' water being equally shared. And both governments agreed to consult before arranging any future use of water internally or any agreements with other Nile Basin governments upstream. A number of natural and political events have occurred in the past four years which have demonstrated the inadequacy of the Nile to meet the expectations of the signatories of the 1959 Agreement. First the drought in the 1980-87 period in the upper catchment - in Ethiopia and the southern Sudan - reduced the annual flow of the Ethiopian Nile tributaries by approximately 20%; these tributaries provide about 80% of normal Nile flow for the northern Sudan and Egypt. And secondly the relationship between Egypt and the Sudan has deteriorated with the change of government in Khartoum to such an extent that in December 1991 representatives of the Ethiopian and the Sudanese Governments reached an accord indicating that there would be agreements on water between the two countries. Throughout the period since the completion of the High Aswan Dam in the early 1960s the relationships between the Egyptian and the Sudanese Governments were generally very cordial and the inter-government Permanent Joint Technical Commission had few problems to address as there was sufficient water in the system until 1973 and since that date the United States has assisted Egypt to meet its food gap caused by the growing water gap. While Egyptian officials are understandably concerned about plans to use water upstream, any problems deriving from adjustments to Nile flow and water quality through increased use are, for the foreseeable future, minor compared with the current water deficit caused by the increased water demands generated by population increase and Egypt's propensity to reclaim new land for irrigated farming. To argue that Egypt will not continue to make the political adjustments which have been witnessed since the mid-1970s seems as perverse as suggesting that Egypt would embark on the hopeless course of securing its Nile water militarily in the long term. In the short term Egypt will adjust to the political economy of water by accepting the economic assistance, and particularly the food assistance, of the United States. In due course it will generate the capacity in its non-agricultural sectors to enable it to expand its purchases of food on the world market.

The tension over the international allocation of water in the Tigris-Euphrates catchment is also less immediate, and at the same time less long term, than suggested by a number of commentators. (Naff and Matson, 1984; Stoll and Starr, 1987; Kolars and Mitchell, 1991) Shortages of water are predicated on the assumption that Iraq will need to utilise water in its agricultural sector. The current economic crisis has political causes and is not related to shortages of water resources. When Iraq re-establishes a stable economy based on oil-generated income it will also resume its import of food staples and other food types and it will not have the urgent or destabilising need to produce food from its difficult-to-manage land and water endowment. There is sufficient water in the Euphrates system to provide water for Syria's agricultural development plans even if Turkey reduces the flow of water by the proportions realistically estimated. Meanwhile Syria will in due course re-examine its water allocation policy and its management of water and may conclude that allocating water to agriculture is neither economically nor ecologically sustainable. It will certainly not take military action against Turkey to secure its water.

Hydropolitics are believed to play the biggest role of all in the Jordan catchment. Water resources are correctly judged to have been one of the factors contributing to the military events of the 1947-67 period and to the continued military presence of Israeli forces in the West Bank and southern Lebanon. The reason that there are severe shortages of water for the populations of the Jordan catchment is that the water allocations to agriculture take over 70% of the national water budgets of Israel and Jordan. The allocation of water according to principles of returns to water would shift water from non-viable economic activities such as agriculture to uses more economical of water. The brief adoption of this policy during the summer of 1991 by Israel will be re-installed by Israel and adopted by Jordan once the diverting imperatives of the Peace Talks have been negotiated. In the Jordan catchment as well as in the other much bigger catchments the non-military adjustments to water shortages have been significant and they will play an increasing role in the future. In the case of the Jordan the willingness of the United States to sustain its support of the crucial economy has been and will remain a major factor in maintaining economic stability by making possible substitution for the evident water shortages.

ACTUAL ADJUSTMENTS

The water resource allocation and management options appear to be very bleak. How then is it possible to argue that there are substitutes for water? The answer is partly that they have already been found for the country with the major water problem in the region, Egypt, and many of the other countries either have no real problem even if they are seriously misusing their water resources. The position can be summarised in Table 3 for the approximately 330 million people of the Middle East and North Africa and for the 20 countries of the region:

Notes on Table 3:

Countries self-sufficient in water or able to purchase food

1. Turkey and Sudan may have economic problems but they cannot be attributed to their water resource endowment. The Lebanon does not have serious water problems but does of course have serious political problems which make investment and institutional development difficult.

   c. 85 million people, c. 26% of the region

2. The relatively low population oil-rich countries - Iraq, Saudi Arabia, Libya, Kuwait, UAE, Oman, Bahrain and Qatar have no real water-resource problems; they only arise if they decide to allocate water to agriculture. They will for the foreseeable future be able to acquire food from the world market. They should certainly not be using scarce water to raise food at a period in economic history when food is being traded cheaply. Iraq has temporary problems.

   c. 45 million people, c. 14% of the region

3. The relatively large-population countries with oil, Iran and Algeria, have serious agricultural problems and Iran has political and international relations circumstances which means that it does not fall into the same categories as the other oil-rich countries or into the protected category of Egypt. Iran will need to address both its traditional sector farming and its modern sector pursuing policies and practice based on the five guiding principles and goals listed above. Algeria has similar agricultural choices to those of Iran although it does not have a well watered province such as Iran enjoys on the southern shores of the Caspian. Oil revenues have not enabled Algeria to mobilise successfully its scarce agricultural resources and it will require particularly effective policy formulation and implementation if it is to create a viable rural economy on the basis of its scarce water.

   c. 82 million people, c. 25% of the region

   The above countries comprise 64% of the total population of the Middle eastern and North African region.

TABLE 3
Classification of Middle Eastern countries by population and resources - water and competence to import food (population data for 1990)

Country	Population '000	% of total regional population	%
COUNTRIES SELF-SUFFICIENT IN WATER OR ABLE TO PURCHASE FOOD			
Water surplus			
Turkey	56 277	17.1	
Sudan	25 191	7.7	
Lebanon	3 000	0.9	
Total	84 469	13.6	
Major food importers competent to purchase food			
Iraq	18 914	5.8	
Saudi Arabia	14 902	4.5	
Libya	4 546	1.4	
Kuwait	2 141	0.7	
UAE	1 592	0.5	
Oman	1 554	0.5	
Bahrain	504	0.2	
Qatar	439	0.1	
Total	44 592	13.6	
Oil economies which are major food importers, with serious water constraints and limited purchasing power			
Iran	56 925	17.3	
Algeria	25 056	7.6	
Total	81 981	25.0	
Total of water or economic surplus countries			64.3
COUNTRIES WITH FOOD AND WATER DEFICITS AND FOOD PURCHASING PROBLEMS			
Major economy with water constraints and purchasing constraints			
Egypt	52 061	15.9	
Total	52 061	15.9	
Other economies with food deficits and water purchasing constraints			
Morocco	25 091	7.6	
Syria	12 533	3.8	
Yemen	11 612	3.5	
Tunisia	8 175	2.5	
Israel	4 656	1.4	
Jordan	3 154	1.0	
Total	65 221	19.9	
Total of water or economic deficit countries			35.7
Overall total	**328 323**	**100.0**	**100.0**

Countries with food and water deficits and economic problems which make food purchases difficult

4. The large population country with only modest oil resources, Egypt, is such a special case that its problems have for the moment been solved by politically motivated external funding. The US Government has apparently assumed responsibility for the serious and deteriorating water gap of Egypt by providing grants and loans which almost exactly match the food/water deficit reflected in the progressively increasing food import bill of Egypt.

   c. 52 million people, c. 16% of the region

5. Morocco, Syria, Yemen, Tunisia, Israel and Jordan are countries with significant water resource constraints and with the exception of Israel they have limited ability to mobilise investment to improve water management systems. They will in future have to address their food deficit problems by generating foreign exchange in other sectors with which to purchase food and thereby reduce pressure on their scarce water resources. Israel and Jordan are already, if unwillingly, well down this road.

   c. 65 million people, c. 20% of the region

   These food deficit countries which have food purchasing difficulties comprise only 36 % of the population of Middle Eastern countries.

The above analysis suggests that for the first three categories of countries there is not a serious resource problem if the resources could be effectively allocated and managed. They either have sufficient water or they do not need it since they can substitute oil revenues to purchase food which cannot be produced at home because of water shortages. Two oil economies, Iran and Algeria, currently have balance of payments and political difficulties which are impairing their capacity to develop but will still be able to underwrite their food deficits with their limited oil revenues. The fourth category, Egypt, cannot substitute for water on an economic basis but it has been very successfully substituting for water through the acceptance of political support from the United States since the mid-1970s. While this is not a satisfactory long-term solution, and is even one which the United States probably cannot afford to sustain, it is also very likely that other sources of funding would be available from other OECD countries if the United States signified that it could not continue to fill Egypt's water gap. There is, however, a much clearer message concerning how Egypt itself will substitute for water in future. It will be through the strengthening of its economy in the industrial and service sectors so that they generate the foreign exchange with which to purchase the food needed to feed the country's rising population. This is the normal pattern of economic activity for economies as they develop. OECD investments will be directed to accelerate this process and thereby gradually ensure that Egypt becomes a self-sufficient economy despite its inability to be food self-sufficient. The demographic position of Egypt will continue to deteriorate but there will be a reduction in the rate of increase in population as the economy improves.

The 36% of population of the Middle East and North Africa in the remaining categories is currently exposed to difficult water resource circumstances and these will continue for the foreseeable future. These countries will face the greatest challenges in substituting for water in the short term at least. Two of the countries, Jordan and Israel, are close to recognising the impossibility of allocating the 70-80% of water of the national water budget to agriculture, although there will be many years of tormented Peace Talks negotiations before the policies are put in place. Since agriculture contributes less than 3% to the Israeli economy and about 7% of the Jordanian economy, the real consequences of reallocating water will not be great, although the internal political reactions may be considerable. Syria, Morocco and Tunisia will have in due course to adopt the same reallocative policies through an evolving ability to substitute industrial sector revenues for the deficient water but the move will only come after their existing water resources have been more effectively reorganised. The problems of Yemen are unique in that the water allocation and management institutions require considerable development.

THE FUTURE: FURTHER RESEARCH ISSUES AND DEVELOPMENT CHALLENGES

The conclusions reached in the preceding section are based on a number of assumptions which deserve more detailed study than is possible here. The first major assumption is that there will be sufficient surplus food on the world markets in the short- and long-term futures to meet the demand of Middle Eastern and North African consumers as well as the increased demand from other regions of the world. The evidence concerning future food availability is by no means clear. Studies by the FAO (1978a and b) and the World Resources Institute (1992) indicate that there are worrying constraints, mainly of an institutional nature, preventing the productive capacity of the world's environments from being achieved. Meanwhile there are concerns about global warming and its varying regional impacts. But the evidence here is arguable and as yet inconclusive (compare the varying estimates from a single scientist - Parry *et al.*, 1988; Parry, 1990; Parry and Rosenzweig, 1992) and it is assumed here that the impact of climate change on agricultural production and productivity will not be significant.

A second assumption is that world food prices will remain similar to the current ones. Here the position is not clear as the availability of food will be affected by institutional changes such as EC and US recognition of GATT recommendations on economic support of agricultural sectors. It could also be affected by climate change with as yet very imperfectly understood negative and positive consequences.

A third assumption is that the reorganisation of former Soviet agriculture will also have hard-to-estimate consequences, some of which are likely to be negative initially as agricultural sector institutions adjust, but in due course are likely to be very positive when, for example, major agricultural economies such as that of the Ukraine achieve levels of productivity of EC equivalents such as France. It is estimated that the Ukraine, which was supplying 80% of the food of the former Soviet Union, is only 40% as efficient as France in terms of agricultural productivity.

A fourth assumption is that the political posture of international entities outside the region will maintain policies of economic stabilisation in crucial economies with the consequence that the aggravation of food shortages will not affect particular vulnerable economies such as those of Egypt, Jordan and Israel. It is further assumed that other OECD entities will take up this role if the United States indicates that it is a task better addressed by a number of competent economies.

Since these assumptions are untried, they all require substantial research in order to make more sound analyses upon which to predict the future of global food security. That such externalities can, however, be identified as crucial for the economic and political stability of Middle Eastern countries suggests that they are the factors which deserve most attention. As it is the economic and political context, including economic and political externalities, which will determine the performance of the water using sectors it is desirable that they are understood by all those involved in policy making for the allocation and management of water at all levels as well as by those operating engineering and institutional systems.

These uncertainties aside, there are many other serious difficulties facing the governments and peoples of semi-arid and arid countries stemming from their water deficits. There is some comfort, however, that the experience of the past two decades does suggest that the realities of the political economy of water have been recognised by some individual governments and despite the ill-inspired food self-sufficiency policies which aggravate the position within countries as well as internationally, the tendency is to make adjustments which are conflict avoiding through economic and political substitutions for water.

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DISCUSSION

The discussion opened with a question about the ability of economies to change allocation and reduce demand for water, and led onto the question of whether international agreements encouraged by donors can improve allocations between countries. The general conclusions were that realistic pricing of both water and foodstuffs was necessary to ensure efficient allocation of water. Donors might have a significant role in this allocative process, both within and between countries.

PAPER 3

Managing water resources versus managing water technology: prospects for institutional change

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Summary: Water mobilisation has been the main focus of most state water institutions, usually for broader objectives in agricultural or energy development. This paper examines the prospects for institutional innovation to achieve improved management of water resources, and generate relevant technical and socio-economic data for planning. Shifts from a technology supply focus to a resource management focus are examined for water supply technology and agricultural technology.

INSTITUTIONS AND OBJECTIVES

Institutions evolve to achieve certain objectives on behalf of the groups initiating them. Sadly, water resources management is one social action that many feel should take place, yet rarely has an administration evolved specifically for the purpose. In many countries, mobilising water has been a major government focus, but for various objectives. As a result, not only are there multiple organisations responsible for water but these are often linked into (or even subsidiary to) other institutional frameworks and objectives. Institutions for agricultural development and energy development often dominate the administration of water, although rural development institutions may play a major role in countries also committed to agrarian reform. It has often been difficult to develop an institutional framework to support and integrate domestic and industrial water with these other uses. Not only have needs developed later but interests may be based in the private sector located outside bureaucratic representation and control.

Even more than other natural resources, water has to be mobilised and combined with other inputs before benefits can be derived from it. Although supply of water technology should be part of an institution designed to deliver particular benefits, in many cases institutions have evolved only for this purpose, so that technology delivery often become separate to the operation of technology and support of users. Many new water technologies lie outside customary controls, or have been used specifically as a vehicle for land reform which has broken customary water rights and obligations. This has decreased the ability of many indigenous water resources management organisations to continue functioning. In agriculture, assumptions are often made about farming activities and water application techniques after interventions mobilising water. Sadly, these are often unrealistic, either in themselves, or because anticipated support services may not materialise. All these issues affect returns to investments and the 'values' derived from water use, and prospects to change current priorities in water allocation.

Institutional innovation will be necessary if governments are to make effective choices in mobilising and allocating water, and encourage the release of water from low-value to high-value use. This may involve new actions from existing organisational frameworks, not necessarily new administrative structures. Institutional innovations create differences in access to the benefits delivered by institutions: they should ideally be organised, tested and evolved by controllers and users of the institutions but all too frequently have to be induced. This paper examines the room for manoeuvre of government and non-government organisations to encourage the evolution of more water resources management, and support the empowerment of groups to gain more, or different, benefits from water institutions. It looks first at the changing influence of central government over the organisations implementing institutional objectives in the water field, and then at key areas where an emphasis on water resources management is emerging in organisations once heavily focused on technology delivery. Finally, it looks at the role of data collection and use in promoting a water resources management focus, and in the evolution of institutions.

THE CHANGING PROSPECTS OF GOVERNANCE

To understand options in institutional evolution, it is necessary to remember that government structures reflect very different political options and preferences in bureaucratic and constitutional development, and very different realities for central and local planning. One reason why attempts by donors to encourage water management reform have failed is that donors have wanted to encourage idealised and often inappropriate resource administrations (rarely found even in the west) and property rights inappropriate to local politics and local land and water tenure. Even though it is easy to see weaknesses in an existing institutional framework, it is not so easy to introduce improvements as producers of idealised bureaucratic structures believe.

There have been several changes in both government policies and donor policies over the last decade which affect options in institutional evolution. Many countries have experienced financial reform restricting public expenditure on the development and operation of large water projects. On the one hand, decreasing financial resources increases bureaucratic competition for financial resources. This makes it less likely that new agencies can develop to deal with major planning and allocation problems. The study by Hirji and Ortolano (1991) in Kenya, highlights the major difficulties in creating any meaningful organisation for monitoring of the environmental impact of water developments, despite increasing donor concern for such studies. In Nigeria, the water authorities that once represented an ideal stereotype for regional water planning have been disbanded.

Where withdrawal of financial support has been rapid across both water supply and broader support services, deterioration in public utilities can be rapid, as has happened in several large irrigation schemes (Woodhouse and Ndiaye, 1991). Where institutional evolution at the centre is blocked, and planning capacity decreasing, the role of sector programmes may increase as sector loans become dominant again, raising important questions about the extent of water development planning scheduled outside the country by lending agencies, rather than within national capacity.

On the other hand, financial reform has induced better performance from many agencies. Under the twin effects of financial constraints and donor pressure, agencies have begun to give smaller projects more support. In irrigation, for example, government departments have been persuaded to offer help where there is existing demand, not simply to try to construct new schemes where 'irrigation potential' has been identified. Rehabilitation has been undertaken to address serious supply deficiencies with the understanding that farmers cannot, and will not, cover operation and maintenance costs unless supplies are adequate and reliable. Agencies have become more amenable to the participation of farmers in the design and implementation of schemes, something for which donors have long applied pressure.

The other change over the 1980s is the move, by donors, away from supporting public programmes through sectoral and rural development organisations to a growing emphasis on promoting the private-sector involvement and self-governing organisations or joint agency-user management in large water projects. For example, in Nepal, although various donors supported irrigation and water supply initiatives through integrated rural development programmes or special public works programmes, most work is now focused within the irrigation department. However, in a recent sectoral loan, the Asian Development Bank said it would no longer support the special office for screening programmes in the Agricultural Development Bank of Nepal anticipating that other organisations could provide this service to government departments (Pradhan and Thapa, 1992).

Indonesia has a special programme to turn over small irrigation schemes to user committees, where administrative procedures and training programmes have been developed through a successful partnership between NGOs and public agencies (Bruns and Soelaiman, 1992). However, one major issue is the replication of this experience in a shorter time frame and at lower costs, especially in countries which do not have the same extent of government and non-government organisations, nor the same financial circumstances. Formation of local associations for basic operational and maintenance work is a growing feature in many donor sectoral programmes. However, they are not always successful, especially where the management and cost load on users increases without much extra benefit.

In China, government units once responsible for duties are now encouraged to tender competitively for operation and maintenance contracts in irrigation sectors. There is growing interest in solving scarcity problems within irrigation commands by contracting the management of water at a block basis, with options appearing for private sector activities in operations and maintenance of water supply. However, what is proving problematic is the provision of support services through the private sector. Provision of mechanised services in land preparation and harvesting, and supply of seeds, fertiliser and credit have all been quite problematic (Woodhouse and Ndiaye, 1991). Technical advisory services, either for advising farmers on technology, or assisting state agencies in screening and implementing projects have also proved difficult, especially in areas where infrastructure development is low. NGOs appear to have taken a lead in providing the 'venture' capital that has helped support services develop among farmers. The role that bilateral and international donors can play in helping the private sector development by underwriting certain development costs and risks is still unclear as they have to work through government bodies.

While institutional evolution is taking place to deal with some allocation problems at the local level, institutional development to deal with reallocation at the regional level is proving less successful so far. As Sexton (1990) points out, the problem is not a lack of institutions or data for planning, as is often claimed. The problem is that economic development creates an actual shift in the responsibilities required of institutions. Bureaucracies which have been highly successful in mobilising water now find themselves required to make allocation decisions they are not equipped for, intellectually or politically. A strategy of increasing efficiencies can defer pressures, but eventually efficiency measures become too expensive relative to the value of water. In many countries where irrigation development has been a significant component of national development (and even identity), water resources were initially over-estimated with large quantities of water allocated to quite low-value agricultural output. The political difficulties in reallocating water are serious as many supply organisations have very close structural links with user groups who can block major changes in the structure and duties of institutions.

DELIVERY AND USE OF NEW TECHNOLOGIES

Many water allocation problems have developed through the rapid expansion of water use across the different sectors. However, very particular problems have emerged both through shifts in the availability of new water supply technologies and new agricultural technologies.

Very few governments have maintained a systematic technology policy whereby specific strategies are developed to use lift or storage technologies, or even monitored. One example of the effects of uncoordinated technology changes is Bangladesh, first to shallow wells and then to deep tube-wells, with the result that much shallow lift technology was unusable long before its economic life was over. The technology shifts also raised many (still unsubstantiated) fears about declining water levels affecting investments and equity effects on farmers (Aeron-Thomas, 1992; Morton, 1989). Most countries put no controls on the type of lift technology available in the markets (although import taxes are almost universal) and farmers can often install over-capacity. Even in countries like India, where some states have supported 'state agroindustries' specifically manufacturing pumps for rural development programmes, the limited range of sizes did mean that many small farmers had over-capacity pumps.

Conjunctive use is an increasingly important focus of attention to improve water availability. However, all too often, the strategy is left to evolve as 'joint' use to solve particular operational and drainage problems, rather than achieve any real optimisation (Vincent and Dempsey, 1991). Various strategies have been identified for commands where both canals and wells are present, but practical action depends on the local geology and available yield from wells, and on local political organisation. For example, experiments in Maharashtra, India, showed that farmers' water officials could not close canals periodically to induce groundwater use in certain periods, whereas this has been achieved in China (Sawant *et al.*, 1991; Sun Fu Wen, 1992).

As water becomes more scarce, one major institutional option often cited is changing the property rights that permit uncontrolled development, specifically through the introduction of licensing. However, in many countries legal traditions and political circumstances make this unfeasible and most countries have looked at the control of water use by other means. It is rights to install the technology that have been emphasised or restricted, not rights to the actual resource in the ground, and in many countries there are few prospects in bringing fundamental reforms restricting water rights. Restrictions on siting often exist within the credit programmes which underlie technology of dissemination. Most countries have looked instead at the means to control water use by other means. Effective energy pricing measures are seen by many as essential. However, as wells become deeper and larger, energy costs become substantial. In one tube-well scheme in the Philippines, electricity prices at market value cost farmers equivalent to 20-50% of the dry season yield (Flores and Mejia, 1992), and are still rising. In Tunisia, the government restricts the hours in which electricity is available (Boutiti Raqya, 1991). Although the use of tax incentives as well as fines has been discussed in more developed countries as a means of controlling water use (as it has for fertiliser to limit water pollution) few experiments are operating (Braden and Lovejoy, 1990). Making technology more efficient and less wasteful has actually led farmers to irrigate more land rather than reduce consumption (Boutiti Raqya, 1991).

In the next decade, there may be less emphasis on water supply technology and greater emphasis on realising the benefits from new agricultural technologies in seeds, fertilisers and pesticides. As the limits to water supply and yield ceilings are neared, attention to field-level water management in agriculture must increase. Many are aware of the gaps in research and extension for integrating advice on plant cultivation and water management. Many important issues in water resources allocation and management and efficient use will be debated on farmers' fields, not only in terms of regional water allocations.

Again different concerns emerge in different locations. For example, in Thailand crop diversification out of multiple irrigated crops is seen as an important concern. This reflects problems of inadequate water supply as catchments are increasingly developed or as river regimes change through upstream vegetation change. The Thai agricultural research institutions appear to have launched effective research and extension programmes that integrate irrigated *and* rainfed crops, or paddy with crops with lower water requirements, experimenting with varieties and crop rotations. In Nepal, an integrated approach is less common despite real gains where it has occurred (Whiteman, 1985). This may be because state interest to promote double cropping under irrigation is intense. In Thailand, institutional innovation in sectorally-based research appears high, improving access by, and relevance to, the small farmer. However in Nepal, despite attempts at inducing innovation through IRDPs as well as in sector programmes, actual innovation in agricultural research and extension is variable across the different farming systems and regions.

Elsewhere, for example in the Philippines, poor irrigation infrastructure and water delivery is seen as a major cause in the gap between theoretical yields and actual yields. Many organisations are being exhorted to ever better performance, making sure farmers co-ordinate the supply of water and fertilisers at the optimum for crop growth. Initially the Philippines put major emphasis into contacting and organising irrigators through the use of social organisers but costs and logistics have ended this programme. Now, many irrigation organisations are taking increasing responsibilities as they co-ordinate fertiliser as well as water, and monitor production. There is increasing debate on whether these organisations should have marketing and saving facilities also, making them supply and marketing co-operatives in all but name. The ironies of seeing one of the earliest development initiatives repeat itself (hopefully having learned from the experiments of the 1960s) is not lost on development workers. Nor is it lost on local administrators and politicians who form the main constraint to granting greater responsibilities to what are now seen as 'third generation' irrigation associations.

DATA USE AND DATA COLLECTION

It may seem strange to hear information generation discussed in an institutional context. However, institutions have a fundamental influence on data generation: also changes in responsibilities (and funding) for data collection and data use can trigger major changes in institutional structure. Does the social and economic information exist to provide a basis for major water allocation questions in the future: if not, who will collect it?

One of the key changes of the last decade has been increased attention to the collection of socio-economic information to aid technical design and programme delivery. Most socio-economic information is still collected either alongside specific assistance projects or as short-term contracts for government information, with little long-term commitment to data for monitoring or evaluation. However, there are also many weaknesses in the collection of social information and little research is being done which can assist major water allocation decisions. In many cases, pressures to spend funds available for technical infrastructure force a pace of implementation that rapidly outstrips socio-economic research. This is partly because few organisations employ social scientists on a permanent basis, but also because of the time necessary for many important social investigations. It is not easy for a small village to absorb a large group of social scientists, and real care is necessary in planning for information collection. In locations where considerable secondary data exists, the techniques of participatory rural appraisal have proved of enormous benefit in assessing local requirements for technical interventions and establishing some basic agrarian and institutional features. However, there are still many situations where rapid contact with villages will not yield accurate information, and will not provide adequate information for baseline surveys for monitoring and evaluation purposes. We still need systematic and longer-term social survey work, and many interventions do not support this. ODA has recognised the importance of having social scientists as project leaders as well as team members, but there are still many recognised problems in ensuring social scientists can play their essential role in country programmes.

However, it should be recognised that there are also problems within social research methodology. Michael Cernea (1991) has pointed out that anthropological paradigms and related research methodologies still do not serve development needs that well, and major contributions could be made if anthropologists were less heavily trained in ethnography, took less interest in villages, had a broader base in development studies and took more interest in studying organisations and processes. Social scientists in development get trained more in their work experience than in their courses. Anthropologists do not have a strong reputation for supplying their findings back into a milieu where they can be used, and often prefer to remain critics after the event rather than accept leadership roles. This may be one reason why, even when considerable information is collected, it may not be systematically organised to feed into programme design or monitoring and evaluation needs. While the hiring of successive different social consultants often fails to give continuity of information, equally the design and reporting of surveys is often weak.

Meteorological and hydrological information has always been an important focus of data collection, but shares many of the criticisms directed at social science training in development. Field workers have long been aware that there are many problems, not only in the absence or presence of relevant data, but also that there are major issues in developing models and equations to use available data in a meaningful way. However, the problem is that the studies that hydrologists want to perform are often not what is required for practical planning, or scientific results are not disseminated in accessible language.

One of the saddest results of the institutional focus on technology delivery rather than resource management is the poverty of the hydrological and environmental database, and the poor availability of relevant assessment techniques. After over 30 years of interventions in many countries, one must wonder why engineers still have to use very rough empirical techniques. One must also wonder why most hydrological training courses still teach so few of the empirical techniques that have to be used in many regions. Why has the hugh emphasis on construction not generated more systematic and relevant hydrological methods? For example, in Nepal, there are now several manuals on appropriate construction in hill areas related to local needs, but there are no equivalent training programmes for relevant hydrological assessment. Can it be because feasibility surveys are still so strongly associated with consultancy companies, or that, until recently, few donors have looked to introduce or develop relevant data collection in programmes which governments could take over? While some promising data-support programmes have evolved, we know little about which activities can best survive the funding crises and even wars that have often affected these programmes, and more accessible documentation would be useful.

The established systems that do exist remain strongly influenced by the donors that have assisted them so that data-sets wax and wane with project inputs. In India, for example, there are massive differences in staffing patterns and data collected across regions and sometimes catchments, reflecting different donor inputs and concerns. Often donors tried to establish an ideal programme of data collection for detailed catchment monitoring, unrelated to specific end needs or the practical funding capacities of countries. In reverse, sometimes the data collection system has become so geared to a certain end result, it is not useful for other purposes. In India, groundwater evaluation procedures are geared to identifying sites where new pump technology can be installed and continue in use even though compilation procedures are now widely recognised as too empirical.

In areas where data collection systems are well established, storage has become a major problem and a lot of material is starting to disintegrate. Both the volume of existing data and increasing financial restrictions mean that a radical review of data networks is feasible and necessary. However, a number of critical institutional and social issues influence the likelihood of changes in data collection systems and responsibilities. Often data collection organisations are under financial pressure - reform is threatening to their very identity. Computerisation is one answer to the data storage problem. However, it centralises available information which often fails to flow back to the field. This not only 'de-skills' the field worker who once analysed the data and removes his/her few creative jobs: it also removes information from the main contact point for the farmer and local administrator. Also, a considerable amount of data (for example, pumping tests and resistivity assessments in groundwater assessment) is not easy to computerise.

Complicated hydrological models may help to demonstrate general surpluses and deficits but these models need to be explained, with real opportunities for users to ask questions. They must also be inter-linked with improved studies of changing demand for water. Although it is now more common to find researchers holding a workshop to explain their results, there is rarely any systematic study of the subsequent use of information by administrators. Many local agencies have avoided the use of external agencies who can do sophisticated models and drilling tests because of their expense and lack of feedback. They prefer to use a combination of simpler, locally documented information, often in conjunction with remote sensing data showing geological and geomorphological features.

Are data analysis systems providing what is needed? Often the answer is 'no'. In groundwater, for example, methods exist to assess general yield parameters and regional aquifer resources, reflecting this major institutional bias in technology delivery. However, we still cannot tell a farmer accurately how the waterlevels in his well will fluctuate across the year, or how to adjust the pumping rate. While there are situations where more data may be necessary, better use of existing data is more important. Preservation of data must be linked with training for key operators in the field, not simply computerisation for easy modelling; and analysis must equally be linked to users. Such changes will raise difficult questions as organisational frameworks change relevant to the financial and political climates of the future.

CONCLUSIONS

Institutions for water resource management do not automatically require a single administration; and there is no such thing as an ideal administration, as needs evolve over time. The historical sequence of perceptions of benefits from water explains much of the structure of existing institutional controls over water, while the history of technology delivery, both in the public and private sphere, often explains many of the dilemmas for solving growing water shortages.

Prospects for improving water resources management and allocation are more likely to evolve through interacting organisations, as most countries have neither the political nor financial capacity to introduce an over-arching administration. These prospects depend on institutional innovation that not only encourages better interaction across and within the various bureaucracies involved in water, but also encourages evolution of more self-governed, jointly-managed and privately-managed activities. While many governments are aware of financial and political dilemmas in changing bureaucratic capacity, most have unclear objectives in decentralisation and deregulation of existing powers, and in the creation of new responsibilities in water management within these new institutional frameworks. While financial reform may actually give donors greater potential to support effective sectoral programmes, donors can also play a major role in supporting these broader innovations outside the state sector. There appears to be more scope for relevant resource management at the local level in many countries.

While people often think that water scarcity problems are emerging due to increased demand, choice and performance of technology - both in mobilisation and delivery of water, and in related production technologies - have a significant influence on the rate and scale of changing water demand, and future development options. Effective water management must consider not only water technology but also catchment management and research, extension and support to improve water use. In agriculture, this means initiatives that integrate water management and crop growth in ways relevant to local farmers: this could mean crop diversification, or more integrated and inter-disciplinary advisory services, or more integrated support services that have good links with extension. In domestic water supply, hygiene awareness is essential to get the benefits of greater supplies. Monitoring technology choices and improving their delivery of benefits may become a much stronger requirement of these new institutional frameworks in the future.

Issues of water allocation and environmentally sound water development and use will have to be addressed within these interacting organisations. Thus effective and relevant training and data collection to support these new policy objectives and changing organisational structure become even more important. Increasing the awareness and information on socio-economic issues remains essential to create an enabling environment for water resource management. Training of technical staff to increase awareness of social issues and the importance of social survey is important. However, encouragement of relevant research and training for both social scientists *and* technical staff will be essential to achieve water interventions that are economically and environmentally sound. Relevant information and planning capability will be as, or more, important that conventional technical assistance in the next decade to achieve better management of water resources.

Finally, while new technical assistance and 'action-research' programmes may be necessary to answer these new policy challenges, much can be consolidated and learned from existing experience. Past donor programmes could be studied for institutional comparisons of the ways they have worked, not only their technical outcomes. Equally, studies of institutional evolution in countries where positive changes have taken place might demonstrate much about the forms of donor support that are most effective.

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DISCUSSION

Much of the discussion centred around appropriate donor interventions. The speaker emphasised that both donors and governments needs to look at the lower levels of bureaucracy. Also that our analysis of institutions for prescriptive advice is very poor, especially at the middle level between national planning and water users. The role of co-operatives was questioned when experience with them has been so depressing. However, the state is handing over irrigation systems to such groups in many cases, but practical powers must be given to these organisations. The issue of whether organisational structures should match the nature of the water resource - lake, river system etc. was raised, but in reality management skills often do not develop for particular hydrological systems. As institutional conditions change, we have to change hierarchies too, but they should not be superimposed.

PAPER 4

Water as an economic resource

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Summary: The growing scarcity of water and the increasing environmental costs entailed by its provision, use and disposal are aggravated by a failure to treat it as an economic commodity. Traditional attitudes, based on supply-orientation and reliance on non-market controls, have contributed to the problem and cannot cope with the problems ahead. Although the obstacles are recognised, it is argued that what is needed is a combination of measures at three levels - the creation of enabling conditions, providing incentives and encouraging markets, and direct project interventions. Various suggestions are made for making the reforms more acceptable to the public.

WATER AS A COMMODITY

Water may be a gift of nature but it is also a commodity. In the economic sense, this is a good or service exhibiting scarcity; unlimited amounts are not available at zero cost. Even where water is plentiful it has to be treated and distributed, and wastewater has to be safely disposed of. These activities use up economic resources. In many - perhaps most - countries at all stages of development, water is scarce and is rapidly getting scarcer. In many cases, the limits of existing supplies are being approached. More frequently, new supplies are only available at sharply increasing costs. In a recent review of projects in the water sector, the World Bank estimated that the cost of a unit of water from "the next project" was often two to three times the cost of a unit from the "current project" (Bhatia and Falkenmark, 1992). These costs are carried by water utilities and their sponsoring government agencies, the majority of which are in poor financial condition and unable to contemplate the large investments envisaged on current extrapolations: $ 10 billion is currently being invested annually in improving water supply and sanitation in developing countries. Even at current costs it would take five times this amount to provide universal reasonable services by the year 2000. Internal cash generation financed only 10% of the cost of World Bank-funded water projects in 1991 (World Bank, internal estimates).

The environmental costs of growing supply and consumption of water are mounting and in many quarters becoming unacceptable. The construction of dams and reservoirs, inter-basin water conveyances, the depletion of natural lakes, and the drawing-down and contamination of aquifers are all causing serious environmental concern. Many agencies have all but suspended aid for large hydro schemes and major water conveyance projects are coming under the closest scrutiny. Pollution from effluent, wastewater and sewage is another source of environmental cost from water use, in this case an 'externality' forced onto third parties. It amounts to using up the finite assimilative capacity of the aquatic environment, leaving none spare for other users and forcing high cost treatment on the public services. Alongside the mounting cost of supplying growing populations and servicing the rising proportion of urban dwellers is the large and growing backlog of services to the poor. Despite the achievements of the UN's Drinking Water and Sanitation Decade, over 1 billion people still lack access to safe water and 1.8 billion to proper sanitation (World Bank, 1992).

These symptoms all lead to water stress and user conflicts as interested parties contend for limited water supplies or for the preservation of threatened environments.

> "..a large irrigation project in India does not operate because water has been diverted to the rapidly growing city of Pune. In China industries are having to reduce their production due to water shortages even though they are surrounded by paddy fields. In California selenium salts leached by irrigation are killing wildlife. [World] Bank

irrigation projects in Algeria are now competing with Bank urban water supply projects for the same water, and many proposed irrigation projects and most hydro project proposals are on hold because of environmental concerns." (Rogers, unpublished).

OUTMODED APPROACHES TO PLANNING AND PROVISION

Water is universally scarce yet the majority of societies do not treat it as such. A commodity should be priced so as to cover its cost of production and to ration its use to those placing the highest value on it. Commodities are bought and sold in markets. Private agents are active in supply and distribution. In a well-functioning market, the benefit attached to the use of the marginal unit of the commodity (the last one to be sold) is the same for all consumers. These conditions are evidently not those in which water is supplied and used in most cases. The water sector is typified by supply-oriented provision, reluctance to make active use of pricing, allocation by non-economic means, the persistence of low-value usage in important sectors, and the minor role played by private enterprise.

In most countries, the automatic response to water stress is to consider supply augmentation. The equivalent of the Hippocratic Oath for water engineers is to promise to meet all reasonable needs for water without question by enlarging and improving supplies. Prices are rarely used to allocate water supplies or to manage demand actively. Water pricing is usually seen purely as an aspect of cost recovery and in many cases (e.g. agriculture) does not even achieve that. The resulting paradox is that an increasingly scarce resource is subsidized, discouraging conservation or the reduction of waste. The average tariff in World Bank-financed water projects - probably a better-than average sample - is only about one-third the average incremental cost of supply. Most authorities respond to scarcity by non-price devices, such as rationing, prohibited uses, exhortation, or cutting-off supplies. Although these can be effective, they can also be costly and inconvenient to users, and do not take account of the relative value of water in different applications.

The benefits from using water typically vary widely from one sector to another as well as within sectors. Variations up to a factor of 10 or more are common in comparing the value of water for different uses within the industrial and agricultural sectors and similar differentials apply in comparing municipal and agricultural use values (Gibbons, 1986; Bhatia and Falkenmark, 1992). This is a sign that total benefit could be increased from reallocating supplies. Another sign of the under-development of markets is the minor role played by private enterprise in bulk supply and distribution. It is no accident that privatisation has made least headway in the water sector and, except in the UK, it has largely taken the form of concessions and management agreements rather than full-blooded ownership.

WHY IS A SCARCE RESOURCE UNDERPRICED AND UNDERVALUED?

There are a number of reasons why water is not treated as other commodities and why water markets are so poorly developed. Why does water differ from electricity or bread?

- Customary attitudes are a primary obstacle in many cases. The idea that water is a gift of God is cited as an obstacle to pricing in some societies (it is less clear whether a dam, a treatment plant, a distribution pipe, or a tap are also due to divine providence). It is understandable that consumers used to getting free water from traditional, unimproved, sources (wells, streams) may resist paying for improved supplies, just as unmetered consumers resist paying proportionately for metered supplies. Whatever their justification, popular attitudes to water constitute a political hurdle to rational pricing. Because water is universally used, the inflationary effects of introducing pricing also need to be considered.

- The fact that water supply is in many circumstances a natural monopoly explains why public agencies are predominant. Difficulties of regulating private monopolies (e.g. in the UK) also account for the limited progress made by full privatisation. Public agencies can and do behave like private enterprises, but mostly don't. In general, water utilities fall far short of normal commercial behaviour.

- Institutions in the water sector have evolved to enable their employees to be rent seekers. Wholesaling water at below its market value to intermediaries and retailers is profitable to the parties involved (though not to the consumers reliant on vendors, who are amongst the poorest urban dwellers). The gains from monopoly power are shared in various anti-social ways. Transaction cost analysis has also produced insights into why the water sector resists market processes (Nickum and Easter, 1991). In certain towns in Ghana a political party extracts half the revenue from charges on the use of public toilets (Lovei and Whittington, 1991).

- Strong vested interests dependent on cheap water conspire to preserve the status quo. Irrigated agriculture and industries reliant on large volumes of water or cheap hydro-power can exercise great political influence.

- The physical barriers to developing a more integrated water market are often crucial. There may be no practical method of transferring water which is surplus to one sector - or used wastefully - to another which could make more economic use of it. In Beijing, surplus agricultural water would need to be collected from groundwater wells and pumped uphill to the city. This sets a limit on how much could be transferred (East-West Center, 1988).

- The physical barriers to the development of water markets are often underscored by legal obstacles, e.g. the existence of long-term entitlements to cheap water, ambiguity over the ownership of water, etc. The rights of third parties in water transfer cases is another consideration and, indeed, is a necessary part of recognising and 'internalising' environmental concerns into the transaction.

- Shifting water onto a more market-oriented basis entails transitional costs which can be heavy. Metering involves a heavy resource cost, which has to be weighed against expected water savings. Industries may need to spend sizeable amounts on recycling equipment or even introducing an entirely new water-efficient process. In households, campaigns to promote water-efficient devices are costly and time-consuming. Socially, ensuring the transfer of water from one sector to another may be disruptive (e.g. may lead to a decline in irrigated farm communities).

Notwithstanding the force of all the above factors, possibly the fundamental obstacle to treating water as a commodity is a lack of faith in the efficacy of economic instruments. It is widely believed that the price elasticity of demand is simply too low for water pricing to do an effective job in restraining demand and reallocating supplies.

TURNING WATER INTO AN ECONOMIC RESOURCE

The interrelated problems described earlier call for action to recognise water as an economic (namely, scarce) resource, and to promote market-oriented reforms in the way it is supplied, used and disposed of. Action is called for at three levels: the creation of enabling conditions; setting incentives and promoting markets; and direct interventions and spending programmes (Winpenny, 1992).

Enabling conditions

In this context, the Enabling Environment comprises institutional and legal changes, the reform and privatisation of utilities, and sector-wide economic policies.

- *Legal reforms* may be necessary to remove ambiguities over the ownership of water and the conditions under which it can be transferred. Planning for the development of water resources - usually dominated by the projection of fixed 'requirements' and the inevitable rise of 'gaps' - needs to adapt to demand management and allow for the operation of markets and, even, the entry of private operators.

- *Water utility reforms* would require them to behave more like commercial undertakings. This will require them to adopt more active pricing, metering and tariff restructuring, improved cost-recovery, and greater self-financing. This will often entail managerial and organisational reforms. Drawing up corporate plans ('contrats-plans') with the government has been shown to be useful in some cases. Privatisation is appropriate in some instances, though it can take many forms and full private ownership is an extreme - and rare - variant. The French model of concessions and lease contracts has influenced a number of developing countries, e.g. Morocco, Cote d'Ivoire, Guinea, Thailand and Malaysia. Regulated private companies also operate in Santiago de Chile and Guatemala City (Roth, 1987).

The best intentioned and designed reforms in the water sector will be frustrated if key economic signals prove to be countervailing. The more rational pricing of irrigation water will be negated by artificially high farm-support prices. Penalising wasteful industrial water use by pricing and effluent charges will be nullified by high protection on the output of heavy industry and 'soft' budget constraints enabling parastatals to pass on increased water charges and fines to their sponsoring ministries. Hence in those countries where water is becoming the scarce factor of production, action in the water sector should be consistent with other key economic signals.

Incentives, market creation and non-market inducements

The permissive effects of enabling conditions may be sharpened by the creation of incentives for the more rational use of water. These may be positive or negative, market or non-market. They will be categorized below as: tariffs; pollution charges; water markets; and non-market inducements.

Tariffs: Although water tariffs are in widespread use in countries at all stages of development, they are usually seen as a means of cost recovery rather than a way of actively managing demand. The principles of economic tariff setting are well established and accepted, and are similar to those in use in the power sector. They can be summarized as setting prices according to Long Run Marginal Costs. This usually entails adjusting the structure of tariffs to include a fixed and variable element, with the latter rising for successive increments ('progressivity'). There is evidence of enough elasticity of demand in the household sector to make tariffs an effective instrument for water demand management. A consensus is emerging from a variety of empirical studies that the price elasticity of demand for water by households falls in the range -0.3 to -0.7, implying that a 10% increase in prices leads to a fall in demand of between 3% and 7%. (Boland, 1991; OECD, 1987; Gibbons, 1986).

A pre-condition of economic tariffs is metering which is not always feasible or sensible. It is also difficult to apply to groundwater users - though there may be good environmental reasons for levying some charge on groundwater extraction.

Pollution charges: Setting economic charges for water may also be the best way of discouraging industrial water pollution by penalising excessive water intake. For example, in two private Indian fertilizer companies of a similar size, the one paying a high price for its municipal water achieved a unit water consumption per tonne of nutrient production only 40% of that in the other company, which depended partly on its own wells and partly on low-priced public supplies (Gupta and Bhatia, Unpublished).

The application of pollution charges proportional to the volume and quality of effluent is more rare, but has been shown to be effective in reducing water intake as well as discharge. In three industries in Sao Paulo, Brazil, the introduction of an effluent charge led within two years to a 40-60% reduction in water consumption (Miglino, 1984).

Water markets: There are various types of water markets. Their common feature is that water can be bought and sold, thus enabling it to find its highest value use. Groundwater markets are long established and widespread in certain parts of the Asian sub-Continent, e.g. Gujerat, Bangladesh. Farmers sell water surplus to their requirements to those in deficit. Surface-water markets exist in some Western states of the USA and Eastern Australia, principally to transfer water from low-value irrigated farming to urban consumers. Sometimes the transfers are semi-permanent arrangements, e.g. the efforts of the Los Angeles MWA to acquire long-term water rights from its agricultural neighbours.

Less well-known are the fledgling industrial water markets in India, whose existence depends on growing supply uncertainty and/or higher costs, together with variations between companies in the feasibility and cost of tertiary treatment of wastewater. In Jamshedpur, India, an integrated steel plant (TISCO) sells water at cost to other Tata firms in the area, as well as to a Birla subsidiary (Bhatia *et al.*, In press).

Water auctions, although unusual, are well-established in parts of Spain and have been tried in Australia. Water banking has also been tried: as a response to the recent drought, the state of California bought up water rights to farmers to hold in reserve for urban and industrial use (and most of the stock was drawn down for these purposes).

Non market inducements: Despite the emphasis in this paper on the value of economic instruments in managing water resources there will always be a role for non-market devices, often working in tandem with economic measures. Education and publicity campaigns can help to convert the public to the need for water conservation, though the message will be powerfully underlined by the use of tariffs. In water pollution, some contaminants are so dangerous that they should be banned - pollution charges are not enough. The only feasible response to short-term emergencies may be to ration supplies and ban wasteful uses.

In authoritarian societies the combination of prescriptive norms, approximating 'best practice' or reasonable usage in each case, and penal charges for users exceeding these norms, can be effective. In Tianjin, China, for example, norms are set for industrial consumers based on regular detailed water audits, and users who exceed their quotas pay a penal water charge of up to 50% the normal level (Bhatia *et al.*, In press).

Direct interventions and projects

The lowest level of the tier consists of direct intervention by the government or water utility to bring about the necessary conservation without further ado. This category of measure usually entails public spending and absorbs administrative and technical resources. Many of these interventions can be thought of as projects. Examples include: canal lining; programmes to reduce unaccounted-for-water (UFW); and the dissemination of improved household appliances. For public enterprises, the analogous action would be spending on recycling equipment.

OVERCOMING THE OBJECTIONS; THE ART OF REFORMING THE WATER SECTOR

It is safe to predict that turning water into a commodity will be controversial and call upon every ounce of a government's goodwill with its citizens. Governments should, however, seek every opportunity to remind their citizens of the alternative - which in many cases will be a grim scenario of growing and eventually disastrous water stress.

The following can facilitate public acceptance of the necessary reforms:

- Exploit complementarities and create synergy between the different elements in a reform programme; create virtuous circles

The profitability of UFW programmes is increased if tariffs are set at realistic levels. Consumers will more readily espouse water-efficient appliances if tariffs are at economic levels. Consumers will be more ready to pay higher tariffs if they see evidence of improved services. Industrialists are more ready to pay pollution fines and charges if the funds are earmarked for visible environmental clean-ups. A vigorous public campaign stressing the value of water and the dire consequences of allowing present trends to continue should form part of any reform programme.

- Create gainers as well as losers

The most effective way of doing this is to promote water markets. Farmers who decide to sell their water instead of using it on low-value crops are doing themselves, as well as society, a favour. There are many interests to be mobilised in favour of pollution penalties and reduced industrial water use: one firm's effluent is someone else's intake.

- Make the reforms socially equitable

In developing countries the poor are among the worst victims of existing systems. They regularly pay prices per unit for their water (from private vendors) many times higher than those paid by wealthier people with their own connections. Any reform that raises charges, improves cost recovery and generates funds for expanding and improving the system promises to be socially equitable, even if charges to piped consumers are raised. The structure of tariffs can further promote distributional goals by offering low 'lifeline' rates for minimum levels of consumption.

- Exploit environmental benefits

The better management of demand will postpone, or even obviate, the need for investment in new supply - with its attendant environmental costs. Reduced water stress will also alleviate user conflicts - between municipalities and farmers, power utilities and fishermen, industrial polluters and recreationists, as well as between nations. A reformed water sector confers environmental, as well as economic and financial, bonuses.

- Enlist private resources

Government has dominated the planning, supply, distribution and disposal of water. This has happened for a mixture of motives, both noble and ignoble. Outright privatisation is not feasible or even desirable in every case, though it is a way of deflecting heavy future costs - and public obloquy - onto the private sector (e.g. the UK). Privatisation stopping short of a transfer of ownership (e.g. concessions, management contracts, contracting out) can combine the advantages of public ownership with private management. The more active use of tariffs and effluent charges will encourage many more firms to invest in conservation and recycling, leaving less of a disposal problem for the public agency. Promoting water markets and raising tariffs decentralises the task of matching demand with supply, and mobilises every party behind solving the problem. Nothing less would seem to suffice.

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DISCUSSION

In response to a question on poverty alleviation, it was said that studies had shown a willingness on the part of the poor to pay for water supply. This seems surprising, but they would save a lot compared to buying from water vendors. So projects should look at wider coverage and fewer public standpipes. Customary attitudes to water supply are exaggerated as an obstacle, particularly by politicians. There are plenty of examples of supposed taboos being broken. It was pointed out that in California and Israel, water is very highly subsidised but very efficiently used. At the other extreme, in Bangladesh, farmers cannot even pay the cost of meters, let alone water. Models of water resources management were discussed; the privatised British water industry was compared with the French system, where ownership is retained but the market opened up; companies bid to manage. This does not throw up the problems of regulation which the UK has acquired. The ancient Roman system was also discussed; but it was suggested that these systems had deleterious environmental effects in the Middle East. It has been observed that subsidised water for farmers is a way of making farmers think that the government cares for them. In discussion it was said that, increasingly, resources are concentrating on the cities; this provides the dynamic for many of the problems which we see (despite the political weight of farmers). Raising the price of water to farmers would create food insecurity. But Egypt, for instance, is wasting precious water on low-productivity outlets. In addition, there was comment on the horrifyingly high percentage of water supply systems now out of use; this shows both lack of consultation and a failure to think through cost recovery.

PAPER 5

Domestic water use: engineering, effectiveness and sustainability

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Summary: A domestic water supply is a basic need required by all, justifying subsidies and donor aid through direct health benefits. This paper considers what sort of water supply is needed to be effective, the role of engineering in water supply provision and an approach to ensuring sustainability.

DOMESTIC WATER USE

Domestic water is used primarily for drinking, cooking, washing and bathing. In some parts of the world an equal amount is used for transporting domestic waste down sewers. The main justification for giving aid or subsidising the provision of an improved domestic water supply is the health benefit. However consumers normally demand improved water supply primarily for convenience, for which they are often willing to pay. Because convenience influences the amount of water used which affects health benefits, these two factors, health and convenience, have to be kept in balance.

At present 1089 million (82%) urban dwellers in the lower-income countries are believed to have a suitable water supply along with 1670 million (63%) of the rural population. However, many of those counted as having an adequate supply suffer because it is inoperable or at best is working only intermittently. In addition to improving existing supplies, the population requiring a new service by the year 2000 is estimated to be 813 million people in the urban areas and 1301 million in the rural (UN, 1990).

Recognising this enormous and continually increasing demand, there are three key issues in domestic water use: What is an adequate water supply and who will have access to it? How can the supply of domestic water be financed and managed? Will there be enough water to meet the 'adequate' demand?

WHAT IS AN ADEQUATE WATER SUPPLY AND WHO WILL HAVE ACCESS TO IT?

It is estimated that diarrhoea caused by inadequate water supply and sanitation results annually in deaths of 4.6 million children under the age of five. Improvements up to an 'adequate' system can lead on average to a reduction in the overall incidence of infant and child diarrhoea by one quarter and total infant and child mortality by more than one half (Warner and Laugeri, 1991). Although children suffer most acutely from inadequate water and sanitation the recent outbreak of cholera in Latin America led to a reported 251 568 cases resulting in 2618 deaths whilst the on-going outbreak in Africa had 45 159 cases and 3488 deaths over the same six-month period (WHO, 1991). In addition, infections such as Guinea worm lead to serious debilitation in adults and loss of productive output, with attack rates ranging from 10 to 40% of the population leaving victims completely disabled for periods lasting 3 to 29 weeks (Smith *et al.*, 1988). In addition to the health problems, many people (almost all are women) still spend hours each day collecting water from a distant source which also leads to a potential loss of productive output.

The agreed slogan for the water sector for this decade is "Some for all, not all for some". Kalbermatten (1991) reports that at present 70 to 80% of funds go to serve 20 to 30% of the population. The population served are mostly the rich who have access to formal housing and also the political power to achieve the average capital expenditure of $ 200 per caput for household water connections and $ 350 per caput for sewerage (Christmas and de Rooy, 1990).

The quantity of water and the proximity of the supply point to the home have been found to be more important than actual water quality in improving health. Even then water supply is only effective when linked with adequate sanitation. Therefore an 'adequate' water supply following the "Some for all, not all for some" guideline will be in the region of 20 to 40 lpcd (litres per caput per day) within one kilometre of the household in rural areas as a first priority and within 100 metres as the second priority (not necessarily at conventional quality 'standards' but following WHO guidelines). In urban areas standposts delivering 40 lpcd within 100 metres are the first priority with yard taps designed to supply 60 lpcd as second priority to meet the health criteria (Cairncross, 1990). To define these service levels as adequate does not preclude higher levels for those who desire them. However the higher water use resulting from house connections with its subsequent increase in drainage requirements should not be seen as a suitable service to subsidise. These 'adequate' levels of water service can be provided for an estimated investment of $ 100 per caput in urban areas and $ 30 in rural areas, a significant reduction in cost.

HOW CAN THE SUPPLY OF DOMESTIC WATER BE FINANCED AND MANAGED?

The estimated investment to meet the demand for an adequate water supply (and sanitation system) from new or unserved consumers in lower-income countries is approximately $ 50 billion per year. Average spending is only $ 10 billion per year and of the $ 3 billion coming from external sources only about 4% is spent on 'low-cost technology' (Christmas and de Rooy, 1990). To put this into perspective, the English and Welsh water companies alone are expecting to invest $ 6 billion this year to upgrade services.

In addition, for existing water supply systems, the World Bank (1990) reports that the average effective sale price of water is only about one-third of the marginal cost of producing the water. This shortfall in finance for both capital and recurrent costs leads to the downward spiral of institutional inadequacy common to many countries. Staff are demoralised because of low salaries and lack of equipment and limited coverage which leads to poor service leading to increased reluctance from consumers to pay even the small tariffs. This, along with erratic government funding, leads to even fewer resources for the sector and even worse service provision and even greater inequity in service coverage. Staff have to promote high-cost technology with external contractors in order to finance the necessary informal (and illegal) additions to their salaries that leads to further inefficiency and waste.

- The major problem of urban domestic water supply is institutional inadequacy linked to lack of finance.

But consumers are willing to pay for water as has been shown by the studies of vendors. One estimate (Cairncross, 1990) suggests that vendors are now serving perhaps 20 to 30% of the urban population with total cost of water at 20% of household income, significantly above the official tariffs and also above the 3 to 5% of income often quoted as acceptable. Clearly even low-income consumers are willing to pay for the service they want. However, public health engineering, as in so much of engineering where 'the professional knows best', has nearly always used a *supply driven* approach. It actually needs to be *demand driven*. This enables customers to show their demand through their willingness to pay for different levels of service. Only when this change is made will it be possible to achieve the required substantial reduction in costs of services (through efficiency *and* the use of appropriate technology) and the equally necessary mobilisation of additional funds from consumers. Jackson (1991) makes the point strongly: "there is no point in dealing with details of engineering design while the financial issues remain unresolved".

It is necessary to finance urban water supply through rising block tariffs with an affordable household 'lifeline' charge for an 'adequate' supply rising to average incremental costs for metered users who want household connections. Only then is it possible to achieve the vital institutional improvements because there is some hope of the necessary funding being available. Once there is general acceptance of the need to raise finance for the sector directly, institutional development has to be considered as the next step in improving water supply. This does not mean adding a training component (or even a 'human resources development' component) to an engineering contract. Rather it means enabling the institution to reform itself so that it can then determine what sort of engineering is really needed. Because it is the institutions of water supply that are failing all around the world which cause the majority of apparent engineering failures. WASH (1988) suggests that institutional development is dependent upon organisational autonomy, leadership, administration and management, commercial and consumer orientation and human resources.

Water supply institutions are most likely to fail because of their place within politically controlled government departments or municipalities. Organisational autonomy (within a politically controlled framework of responsibility and authority) is a necessary pre-condition to effective water supply. New organisational models that use the private sector to a much greater extent such as management contracts or leasing (affermage) are required. Transfer of equity as in complete privatisation will probably not bring significant benefits to utilities in low-income countries in the medium term.

The change that is required subsequent to greater autonomy is a commitment to a commercial orientation. This is not a commitment to profit making or to profiteering but to providing the most efficient and effective service to the whole range of consumers in a commercial style whilst retaining a basic needs service to low-income consumers. This will require enhanced leadership of the institutions and the type of team-building and quality circles and reduction in middle management that has become such a feature of the commercial developed world. It will require the introduction of clear performance indicators and sensible (modest?) management information systems. It will particularly require the upgrading of accounting systems such that there is accounting for fixed assets as well as recurrent costs in order to gain some sort of understanding of the surplus or loss generated from operations in any year. Zero-based or Priority-based budgeting systems will have to be introduced with managers directly responsible for a clearly defined cost centre.

To be effective with a new commercial orientation, institutions also require a new orientation towards their consumers or rather customers. Customers who pay the appropriate tariff have to be cared for and have the right to expect a suitable service.

In urban areas where economies of scale demand integrated systems for water supply (not necessarily true for sanitation) dis-economies of management may demand the separation of the roles of bulk provision of water (production and wholesaling) from the distribution and sale (retailing). Moving the institutional/household boundary back from the property line to some form of site or area boundary can enable a community or private enterprise to take responsibility for managing a distribution network and collection of revenues (retailing). Alternatively the (private?) provision of communal bath houses for bathing, laundry and sanitation is a possible approach to water retailing and on a smaller scale still there can be an individual with a standpost concession.

- The major problem of rural domestic water supply is institutional inadequacy linked to lack of community involvement.

There has been much discussion regarding the need for community participation. Having often failed in this form (community participation became what its name implies, the community participating, often reluctantly, in an agency scheme) the recommendation is now to promote community management. This implies that the community have the responsibility to manage all aspects of their service provision, from planning through finance to implementation, operation and maintenance. This is valid for discrete, community level technologies in rural areas, but the community or household does not always know what they want or what the options are. A new customer orientation stresses the requirement for service ('the customer is always right') but also implies a responsibility to determine (through 'market research' rather than 'social surveys'?) the right product for the right group of people at the right price.

Perhaps what is required is a 'services supermarket' where potential customers can examine the available technologies and discuss possible prices and installation services and credit terms (and available subsidies). This approach can work well for discrete technologies such as rainwater catchment tanks, hand-dug wells, handpumps, ram pumps and on-plot sanitation and can be adapted for communal gravity flow water and other rural development systems.

Some of these ideas might sound familiar as the need to promote efficiency and effectiveness in public services in UK faces similar challenges in becoming more commercially and consumer oriented. The Citizen's Charters, privatisation (in its broadest sense) and internal markets may represent a more useful UK export to low-income countries than sophisticated engineering.

How might this institutional development (revolution?) be achieved? It can be assisted and encouraged by consultants but, like all development, ultimately it has to come from the people most concerned. Therefore ways have to be found to introduce ideas and suggest changes whilst allowing the institutions themselves to find their own way forward within their own political framework.

Consultant counterparts trying to justify their existence by telling institutions how to develop on a daily basis will not be effective. What is required is continuing and more focused support for human resources development - through extension of twinning arrangements, postgraduate courses which emphasise management (MBA for Utilities?), higher degrees by research into management issues, professional networking (as in ODA-supported GARNET), promotion of professional associations, supported by intermittent but regular consultant visits. The aim of all this to enable existing institutional staff to become their own management consultants so that they can bring about effective, sustainable institutional change themselves.

WILL THERE BE ENOUGH WATER TO MEET AN 'ADEQUATE' DEMAND?

There is a growing concern that the dramatic growth in the population of the urban areas will lead to a shortage of water. Undoubtedly bringing a dispersed population together demands a much greater point supply than was needed previously . Engineering can be effective at developing sources ever more distant from a city and transporting water over long distances. Where water sources are limited clever engineering can desalinate but at *high cost.* Domestic water demand management is one way of ensuring that there will be sufficient water at an *economic cost.* The major areas of demand management to consider are the use of technical, social and economic techniques and most importantly the choice of sanitation.

- The use of technology for water saving depends upon leakage control, pressure reduction and the introduction of reduced water-using appliances such as aerator taps and showers and low-flush toilets. These technical solutions are simple and effective though require a significant initial investment. In the case of household appliances some form of promotion is usually required with the support of changes in bye-laws.

- Social techniques of demand management refer to the use of education and legislation. Often these approaches appear to have most value at special times of drought but in the long term, as attitudes towards use of resources change, they may have a significant part to play in continuous demand control.

- Economic techniques depend upon tariffs and metering. For tariffs to have an effect on water consumption they have to be linked with meters. Whilst at first sight it is entirely logical to have a system whereby people pay directly for what they consume, the problem with meters is that they are expensive to install and maintain. There has been a 13% average reduction in domestic water use in the UK metering trials but it is anticipated that this will decrease as coverage increases, for most of the reduction is achieved in the richer suburbs with large gardens. Binnie (1992) also reports that the cost of meter installation rises significantly as coverage increases (the simplest properties tend to be metered first).

If in this country where meter installation would cost only 2% of average annual income we have not yet been persuaded of their value, is it reasonable to expect them to be used in countries where the cost represents 28%? The reduction in demand may not be worth a reported increase in water supply costs of 25% in low-income countries. Alternatives to consider are the use of flow restrictors in delivery pipes or some form of design limitation in pipe size and pressure to limit overall supply to low-income, subsidised consumers. Another approach is to consider the use of district meters with private or community vendors selling on the water as described earlier.

- Although this paper concentrates upon domestic water use, sanitation has to be considered because of the implications for water demand (in addition to the health implications). Demand for improved sanitation by the year 2000 is estimated to be 947 million people in the cities and 1676 million people in the rural areas. If this total of 2623 million is to receive sanitation through conventional means the increased demand for domestic water supply will be insupportable when considering an average four flushes per day at 10 litres (or even a reduced 5 litres) per flush.

On-plot sanitation (very improved latrines or septic tanks) can reduce per caput water demand by between 25 and 50% (as compared with sewerage) whilst providing all necessary convenience, cleanliness as well as affordability. Currently the focus of an ODA research project, many countries still see on-plot sanitation in urban areas as worse than second best. Intriguingly it is reported that in Japan only 42% of households are connected to sewers - "the rest have to make do with septic tanks emptied by suction truck once every few months" (The Independent, 1991).

The major fear regarding on-plot sanitation has been the danger of pollution reaching the groundwater. This pollution is represented primarily by nitrates as pathogens do not normally travel any significant distance. In the successful Maputo sanitation programme there has been a measurable rise in nitrate levels in the shallow groundwater but following experience in other areas with higher than recommended nitrate levels there have been no recognisable health implications. If in the end problems do arise with local deterioration in shallow groundwater quality the figures suggest that it is always more economic to pipe clean water in to a city than it is to pipe wastewater out.

All these techniques show that domestic water demand can be significantly reduced. However, in the context of overall water resources it is necessary to recognise that only 15% of the water abstracted from the hydrological cycle is used for non-irrigation purposes and of that only one third is directly for domestic use. This puts into context the apparently high wastage of 34% average unaccounted for water - especially when it is suggested that 'losses' in irrigation, representing 85% of water abstracted, are of the order of 60%.

The choice therefore becomes clear. In a year, 1000 cubic metres of water may be used *either* to provide water for 80 people *or* to grow food for between 1.6 and 3 people. This imbalance of between 1:30 to 1:50 in the ratio for daily water use to irrigation-grown food suggests, that in the context of competing demand for water, then domestic water use should win every time. It is far more economic to move food from a rain-rich area to a dry area than it is to move water. "In some regions it has been demonstrated that more efficient agricultural irrigation would release sufficient water to meet all additional urban needs" (Okun and Lauria, 1991).

Water for irrigation and for domestic use must be valued as an economic good. If this policy was followed, particularly with regard to groundwater abstraction, then many apparent shortages of drinking water could be overcome.

CONCLUSIONS

To be effective, domestic water supply requires a moderate amount of water of moderate quality as close to home as possible. To be sustainable, water supply requires revitalised institutions that have control over their finances. What are the implications for engineering once domestic water is seen to have priority over irrigation water? This paper has not concentrated on engineering for after all, what is difficult about connecting a power supply and some lengths of pipe to a pump and turning on? This gross oversimplification is meant to suggest that the basic engineering is relatively easy though for the operation and maintenance to remain manageable unfashionable technologies such as slow sand filters must be used wherever possible. Optimisation of the engineering is a challenge - but remains worthless when the underlying problems are institutional.

The extra percentage points of efficiency are only achieved once an effective institutional system is in operation. Even then, engineers must avoid the temptation to concentrate on the functional aspects of planning and think more of the normative aspects. UNICEF imported over a million small plastic taps into Nigeria to fix to water pots. Now that people no longer have to dip a contaminated container into the household water store health benefits are more assured than when the effort went into achieving ever higher 'engineered' quality of water at the standpost. The objectives have to be considered before the means.

To maximise benefits from investment of aid in domestic water use it is necessary to draw back from the engineering and enable institutional development based on commercial and customer orientation. "Capacity building and the institutional and human resources development effort that are integral to it, is essential to provide program and project sustainability" (Okun and Lauria, 1991). Without this targeted investment we will continue to see inadequate and intermittent supplies with the resultant disease and dis-ease afflicting tens of millions.

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DISCUSSION

Several questions were concerned with the relative value of water for domestic, irrigation and industrial use. It was pointed out that some industrial processes, like irrigation, used a great deal of water per unit product and that there is scope for considerably improved water use in many cases. For high-value crops the cash return per unit water could be attractive.

In the light of ODA's proposal to place little emphasis on health benefits during the appraisal of water projects and the speaker's reference to global figures for health improvements related to water supply, he was asked if case histories of such improvements were available. He replied that he was involved in a current West African study to do with reduction in guinea-worm infection following clean water provision.

PAPER 6

Domestic and community water management

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Summary: Domestic water collection and management world-wide is the burden of women; participatory hygiene education for women can improve domestic sanitation and increase hygienic use of domestic water; but for fully effective and efficient use of community water supplies, women must be involved in their management from at least the design stage of the supply.

DOMESTIC WATER COLLECTION AND MANAGEMENT

In traditional cultures throughout the world, the burden of domestic water collection falls on women and older children. This applies equally to moslem cultures that seclude women: there fully veiled women *escorted by* a younger male relative often carry domestic water.

Within the home, management of domestic water is again women's responsibility, whether this is managing an African three-pot system or ensuring adequate supplies in Asian family water pots. It is the women who cook, wash pots, launder clothes, bathe small children, care for the sick and water domestic animals. In some communities, the women carry water for all these purposes to the house whereas in others clothes are laundered and bodies bathed at the water source. Animals may have their own watering spot, but many cultures do not perceive the need for this and share common water supplies with their domestic animals. There are places in Africa where a round trip to collect domestic water takes the women on average three to four hours and they must leave home well before dawn to commence this task. In South Asia round trips are shorter, averaging one hour, but certainly in Nepal and other Himalayan countries this can be over extremely arduous climbs.

A consistent finding around the world is that when water supplies are brought closer to homes, there is not an increase in water usage unless it is brought to within 15 metres of the house. Thus, providing a village tube-well or tap stand alone may have no measurable impact on the people's health since the increased volume of water used is an important factor in decreasing both water-washed and water-borne diseases. The benefits of village wells and standpipes have to be measured by the increased quality of the women's lives: more time to rest, more time with their children, more time for themselves. Economists may say more time for production but that is not necessarily an improvement in the quality of their life.

A key point is that since women have the responsibility for collecting and managing domestic water, any surveys of water usage in a community must survey the women. Questionnaires directed at the men (often the easiest respondents to reach) can only provide haphazard guesses of the quantities of water used and the time taken to collect water each day.

COMMUNITY WATER SUPPLIES

If community water supplies decrease the burden of carrying domestic water for the women, then why all round the world are hand pumps lying broken down and piped water supply schemes dysfunctional or badly maintained? Further, one study by UNICEF in Nepal has indicated that communities drinking from piped water supplies more than two years old have higher mortality from diarrhoeal diseases than communities drinking from newer piped schemes and communities that have never had piped water. This was attributed to contaminated tanks on badly maintained gravity flow piped systems.

In Nepal it is an everyday problem to see standpipes without faucets in muddy, unhygienic environments. Private hose-pipe connections are often made to public standpipes or 'public' standpipes are constructed in influential people's home compounds. Surplus water from standpipes often flows over tracks and trails making them inconvenient to passers by and even dangerous on hill sides. Exposed distribution mains with amateur joins, and even open break pressure chambers with home-made syphons attached are frequently seen. Hand pumps are often rusted and in pieces and most require 'priming' with a bucket of water before any water can be drawn.

At first it was assumed that it was lack of community participation that was the problem, and so UNICEF has adopted the policy of only undertaking village water supply schemes where the communities contributed the labour and local materials (stones and sand.) Their studies have clearly shown that standpipes fitted with self closing faucets are more likely to be damaged and missing the faucet after two years than standpipes fitted with babcock faucets. However, their schemes have continued to be badly constructed with inadequate trench digging and back filling after pipe laying and poorly maintained tap stands.

It is not difficult to hypothesise reasons for this in the light of personal experience working with communities in Nepal. The political system there is dominated by patronage and corruption and local politicians are able to exert considerable compulsion over their poorer community members. The situation is compounded by the Hindu caste system which gives the higher castes subjugative influence over lower castes. Village water supply construction is considered after requests from the political leaders: often leading to supplies for the richest and loudest demanding rather than for those in most need. The richer villages are inevitably those with good indigenous water supplies. The schemes are then surveyed by district engineers and overseers who supplement their incomes by accepting 'gifts' from the villagers - gifts linked to the subsequent siting of tap stands. The engineers and overseers have little or no contact with the women, the main drawers of water, or the poorer sections of the community who often have the greatest need for piped water. However it is the poor who are coerced into portering pipes and cement to the villages and who undertake the bulk of the trench excavating and back filling. As only marginal beneficiaries of the completed water supply schemes, they have little incentive to undertake their tasks with the required rigour.

THE UK/NEPAL EASTERN REGION WATER SUPPLIES PROJECT (ERWSP): A CASE STUDY

Teams of community-based health promoters worked alongside the water supply construction teams raising the communities' awareness of the need for hygienic use of water and improved domestic sanitation if the communities were to fully benefit from their new piped water supply schemes. The Health Promoters, two women and one man, attached to each water supply scheme had been trained in non-formal, participatory education techniques and in communication and community mobilisation skills. Although the health programme has not been formally evaluated, there was considerable popular support for the programme and repeated anecdotal reports from subsequent visitors that domestic pit latrines continue to be in evidence and villagers understand how diarrhoeal diseases are spread.

The water supply construction was jointly executed by the Department of Water Supply and Sewerage (DWSS) and an expatriate firm of consulting engineers. In accordance with DWSS policy, all materials were supplied by the project and construction was undertaken by contracted, paid labour. The labourers were often from outside the area served by the water supply schemes. Within the ERWSP, consumer responsibility was imposed late in the project with no participation in the planning and design stages of their schemes, only the political leaders having any input into the siting of standpipes, and no input into the construction of either materials or labour. As some of the schemes were coming up to commissioning, SEADD requested that the health programme staff implement a water consumer training programme as they had the necessary communication skills, community mobilization expertise and the trust of the local people.

The water consumer training programme was about raising the community's awareness of its responsibilities for its own water supply. This in practice involved communicating new information in a manner that was usable by the people; providing a forum for debate and development of ideas and plans, and a structure through which the consumer could implement the ideas and take responsibility. Water consumer training aims to help the consumers prevent damage to their scheme and prolong the life of the scheme for the health and convenience of all consumers.

Before water consumer training, the schemes suffered from the usual problems of stolen faucets, open faucets, unhygienic muddy environments for the tap stands. In one village, with twice-daily water supply, there was considerable congestion at the tap stands during periods of water supply. Private hose-pipe connections were seen and some of the standpipes had been built on local politicians house forecourts.

Water consumer training was targeted at the women drawers of water and involved establishing water user groups for each tap stand. After water consumer training, there were considerable consumer constructed improvements at the tap stands on all the schemes except one. Improvements included soak pits, drainage channels, enlarged concrete aprons to the tap stands, and in poorer communities that could not afford to purchase cement, wooden laundry platforms. At the festival season, tap stands were painted, decorated with welcome arches and the surrounding area planted with flowers.

Discussions at the consumer training sessions elicited that consumers were often critical of the design of their schemes which they said brought water from a great distance to supply hamlets that already had good supplies of spring water and yet did not adequately supply hamlets that were much drier. They suggested constructing smaller closed systems from the indigenous springs to the well-supplied hamlets, thus freeing up pipes and imported water for the most needy. Further, by siting a reservoir watchman's standpipe outside the reservoir compound, a large hamlet of 'untouchables' could have been provided with potable water which they are denied by siting the tap stand inside the locked compound.

Tap-stand siting was commonly criticised by the consumers who said that the sites were convenient only to the village chairman and his friends. Inadequate consideration had been given to drainage of tap stands, problems which they would have predicted if they had been consulted. Many women complained that tap stands were at the bottom of hills causing them to have to carry full water pots up hill when they would have preferred tap stands at the top of slopes so that they only carried empty water pots up hill. One tap-stand user committee wanted permission to turn its tap stand around by 180° as the women did not want to bathe in full view of the traffic on the road. They were persuaded that this would not be possible but it is to be regretted that they had not been consulted about whether their tap stand should face the road or not. Consumers had many criticisms of the tap-stand design and useful suggestions for improvements: many of which they undertook themselves after training.

The most worrying questions that arose during discussion was what consumers should do if they exposed pipes crossing their land during ploughing. It seemed that pipes had not always been buried at one metre depth and the consumers not only knew this but knew that it was inadequate. However, they had been powerless to do anything to ensure adequate trench digging because they were just 'little people' and did not know how to go about complaining. The consumers were all too often aware of pilfering of cement and other materials and the poor quality of concrete used in tap-stand construction. Again they were powerless to do anything about this malpractice.

In the village that showed no interest in maintaining or improving the tap stands, almost all the houses had hand-dug wells in their courtyards. Hence they were not interested in using tap stands that provided colder water in the winter months and warmer water in the summer months for bathing. They were also not interested in carrying water from tap stands for domestic use when they could use less energy to obtain water from their own wells even when the water table was as low as 30 metres. They repeatedly stated their preference for water piped to their homes but were denied this as it was not current DWSS policy to provide metered supplies outside the metropolitan areas. This policy has now been changed and the DWSS has ceased supply to all the public standpipes on that scheme. It now supplies water only through metered domestic pipelines paid for by the individual consumer households.

In one village, water consumer training was undertaken in two parts separated by several months. Following training at tap stands in the more rural areas, the villagers made many modifications to their tap stands. Those consumers in the bazaar area were well aware of the voluntary activity at tap stands in the rural areas but did not undertake any improvements at their own poorly drained, congested tap stands until after their own consumer training. Then they went on to make modifications to their own tap stands at a grander level than any modifications elsewhere. It was wondered why they had not undertaken the improvements sooner: preferring to endure several months further inconvenience rather than get on with their plans. It seems that the tap-stand users needed the 'approval' of the training programme before they could be empowered to take responsibility for their tap stand from the DWSS, who they perceived as the owners before consumer training.

Thus even with late involvement of the consumer, the ERWSP has demonstrated the value of water consumer training in terms of improved environmental hygiene and convenience to the consumer. It is suggested that early participation of all the consumers in water supply schemes would result in more effective use of available water, less pilfering of materials, improved construction, more appropriately sited standpipes with consequent increased utilization and maintenance and less vandalism of pipelines.

DISCUSSION

There was general agreement that the involvement of water consumers in projects such as the ERWSP should be encouraged at the earliest possible stage.

Discussion focused on the difficulties of organising participatory techniques. The key issue was the existence of rival interests in controlling the water resource. In particular, central government ministries wished to retain control of water supply and had imposed policies which were not always for the benefit of the local people. Within the community there were also potential conflicts between the more influential members of the community and the poorest, and men who were usually more vociferous in public gatherings but who were less involved in water use than the women.

PAPER 7

Pollution alleviation issues: a case study on the River Ganges

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Summary: Thames Water International were employed as technical advisors to the Ganga Project Directorate to assist with the implementation of the Ganga Action Plan, an ambitious plan to clean up the River Ganges. A team of water quality and sewerage experts from Thames Water were charged with evaluating the sources and extent of water pollution in the River Ganges and to assist in drawing up a plan for its control or prevention. In addition to the environmental work the consultancy covered a wide range of disciplines including sewage treatment, sewer maintenance and sludge management. This paper will concentrate on the environmental aspects of the work but relates the findings to the management of sewage disposal. Technology transfer was a major element of this project.

INTRODUCTION

The work was sponsored by the Overseas Development Administration and consisted of an advisory programme between the governments of India and the UK. Thames Water environmental and sewage treatment specialists worked with counterpart Indian scientists and engineers from the Ganga Project Directorate and the State Pollution Control Boards to effect technology transfer and to facilitate the requirements of the Ganga Action Plan. The work contained a number of key elements including the development of a computer model to assist with strategic water quality planning. This was linked to a project to design and procure an automatic river quality monitoring (ARQM) system and to undertake river quality surveys with which to establish suitable sites for the siting of the monitors and to provide baseline data for input into the model. In addition, advice was given on the selection of appropriate sewage treatment options and associated maintenance requirements. Priorities were set for the rehabilitation of sewers and sewage treatment works. The siting and design parameters for new treatment plants were also considered. This work required a significant amount of time to be spent in India, gathering information and gaining an understanding of the current situation and practices.

When undertaking a programme of water pollution abatement a thorough understanding of the river environment is an essential precursor. The physico-chemical and flow characteristics of the river, seasonal patterns, existing pollution loadings and the use requirements of the river need to be known before the siting and design of sewage treatment works can be undertaken. This information can then be fed into a computer programme which is capable of simulating the impact of varying the concentrations of pollutants upon the river.

This paper will concentrate on the environmental elements of this work, specifically the design, procurement and commissioning of the network of automatic river quality monitoring stations and the water quality surveys undertaken on the River Ganges. The work began with the author making a preliminary visit to India in August 1986 and subsequently writing an ARQM system specification. River surveys were carried out in April and May 1987 and February, March and April 1989. Further visits were made in February 1990 and 1991 to test and commission the equipment.

THE GANGA ACTION PLAN

The Ganga Action Plan is best summarised by the following extract from An Action Plan for the Prevention of Pollution of the Ganga, Department of the Environment, Government of India, revised, 1985:

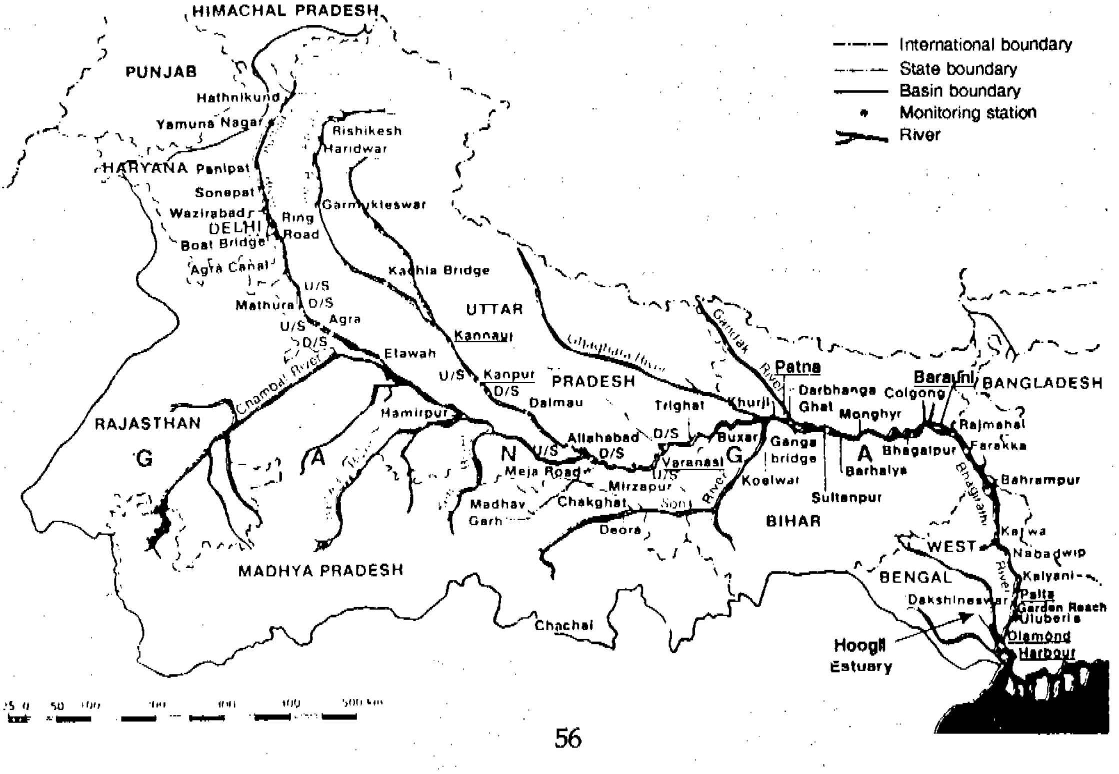
> "Based on a comprehensive survey of the Ganga Basin carried out by the Central Board for the Prevention and Control of Water Pollution (CPCB), an Action Plan for the prevention of pollution of the Ganga was prepared by the Department of the Environment (India) in December, 1984. The Central Ganga Authority (CGA) with the Prime Minister (Rajiv Ghandi) as chairman was set up by Government Resolution in February, 1985. This was a high level body for determining policies and programmes, to allocate resources and mobilise public support for accomplishing the Action Plan. In June 1985, the Ganga Project Directorate (GPD) was established as a wing of the Department of the Environment, to appraise and clear the projects prepared by the field level agencies, release funds and co-ordinate the various activities under the Action Plan on a continuing basis."

The principle aims of the Action Plan are, "the immediate reduction of pollution load on the river and the establishment of self-sustaining treatment plant systems."

GENERAL CHARACTERISTICS OF THE RIVER GANGES

The River Ganges (Ganga) is the largest and most important river in India. It is 2552 kilometres long and carries the drainage of a vast basin of more than 1 060 000 square kilometres, which is bounded by snow-covered peaks of the Himalayas in the north and the peninsular uplands of the Vindya range to the south (Figure 1). It extends over four countries, India, Nepal, Bangladesh and China. It drains 814 400 square kilometres within India, covering more than a quarter of the land area. It is a major surface and groundwater resource with an annual flow of 468.7 billion cubic metres, equivalent to approximately one-quarter of India's total water resource. The Ganges basin is the home of one third (approximately 200 million) of the Indian population and is one of the most important pilgrim centres of India (CPCB, 1984).

FIGURE 1
General map of the River Ganges



SEASONAL AND CLIMATIC CONSIDERATIONS

The subtropical river and climatic conditions are associated with four seasons, characterised as follows (CPCB, 1984):

1. **Monsoon season (June to September)**
   Frequent rainfall, dramatic increase in river level and flow
   Air temperature, 25-40°C
   High humidity

2. **Post - monsoon season (October to November)**
   River flows decline sharply
   Air temperature, 15-35°C

3. **Winter season (December to February)**
   River flows continue to decline
   Occasional bursts of winter rainfall
   Air temperature, 5-25°C

4. **Summer season (March to May)**
   Flows as for winter
   Air temperature, 15-45°C.

This seasonality is reflected in extremes of river depth and flow rate, with the effects being particularly pronounced at Varanasi where the river is constricted by high ground on either side. For example, at Varanasi, during the summer season water depth is approximately 12 metres with a mean flow of 285 cubic metres per second. During the monsoon, depths rise to 20 metres and mean flows increase to 13 454 cubic meters per second.

The subtropical nature of the Indian climate is an important consideration in the design and operation of equipment which must work at high ambient temperatures and variations in air temperature from 5°C during winter nights to 45°C during summer days must be expected.

ARQM SYSTEM DESIGN AND SPECIFICATION

The experience gained from the operation and development of the freshwater and tidal ARQM stations in the River Thames catchment provided the basis for the specification of the system for the Ganges. The format of the tidal system was particularly appropriate because of the simplicity of the *in-situ* (sensors immersed directly in the river) sensor arrangement, designed to operate in harsh conditions which included large fluctuations in water level. Modifications to the format were required to accommodate the subtropical environment and the monitoring needs of the Ganges.

A specification was written for a network of nine monitoring stations to be sited on the Ganges to monitor the effects of water pollution in the vicinity of specified major cities. The stations would be un-manned and would be remote from operational facilities. Mains power would not be available. The project would involve the production of an operational prototype to be tested near Delhi under the supervision of the author. Phased introduction of the nine monitors would follow.

Water quality information provided by the CGA and a review of water quality in the Ganga (CPCB, 1982 and 1984) provided a baseline with which to specify the system. The specification was written in 1986 in the form of an International Tender Document.

Seasonal variations in water level of up to 10 metres had to be taken into account. This factor, combined with unmade banks and the lack of suitable buildings in remote areas excluded the use of fixed stations and meant that a floating platform arrangement anchored to the river-bed or suitable structure offered many advantages. In addition, floating platforms allowed for the possibility of moving outstations at a later date and made them suitable for use on any river in India.

Other factors that had to be taken into account in the design of the floating platforms were as follows:

- provision for anti-fouling measures
- availability and size of craft for positioning and anchoring a platform
- need for specialist advice on anchorage of platforms
- need for the system to be operational during the monsoon, particularly during its 'first flush'. In case this proved impossible, provision had to be made for the removal of the equipment for the duration of the monsoon.

The floating platforms and anchorages were designed in collaboration with marine architects from the Oceanographic Research Centre in Madras. Figure 2 is a schematic drawing of the platform which formed the basis of the detailed design and construction work undertaken by the architects. Figure 3 is a photograph of the equipment in operation on the River Ganges.

Since it was proposed to operate the stations in truly remote locations where mains power would be unobtainable, power consumption had to be kept to a minimum and solar power options were the most suitable choice.

The following factors had to be taken into account in the design of the mounting for the sensors:

- sensors were to be placed directly in the river
- sensors should be mounted on a robust 'lance' assembly to allow for sampling at a depth of 0.5-1.0 m below the surface
- sensors needed to be protected from damaging impacts from floating debris
- sensors needed to be easily removed for servicing and cleaning
- anti-fouling measures
- incorporation of a facility for swinging the probe up and back down in the event of collision with a submerged object.

The ARQM equipment was required to provide the following range of sampling frequencies:

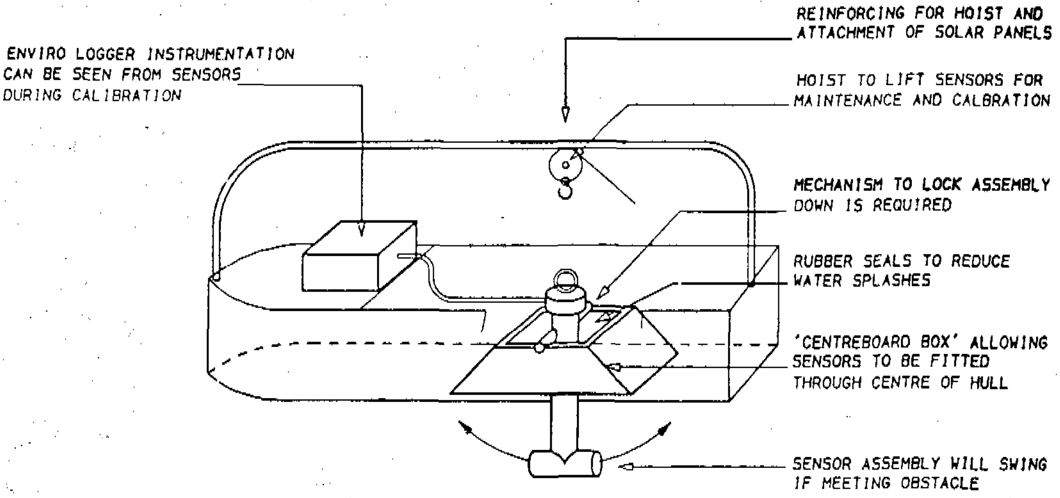
• 24 per day • 12 per day • 6 per day • 4 per day • 1 per day

The actual frequency of sampling that would be employed in long-term monitoring programmes would depend upon trial results. Dataloggers would be provided in the first instance and options to convert to a telemetry system were specified.

WATER QUALITY SURVEYS OF THE RIVER GANGES

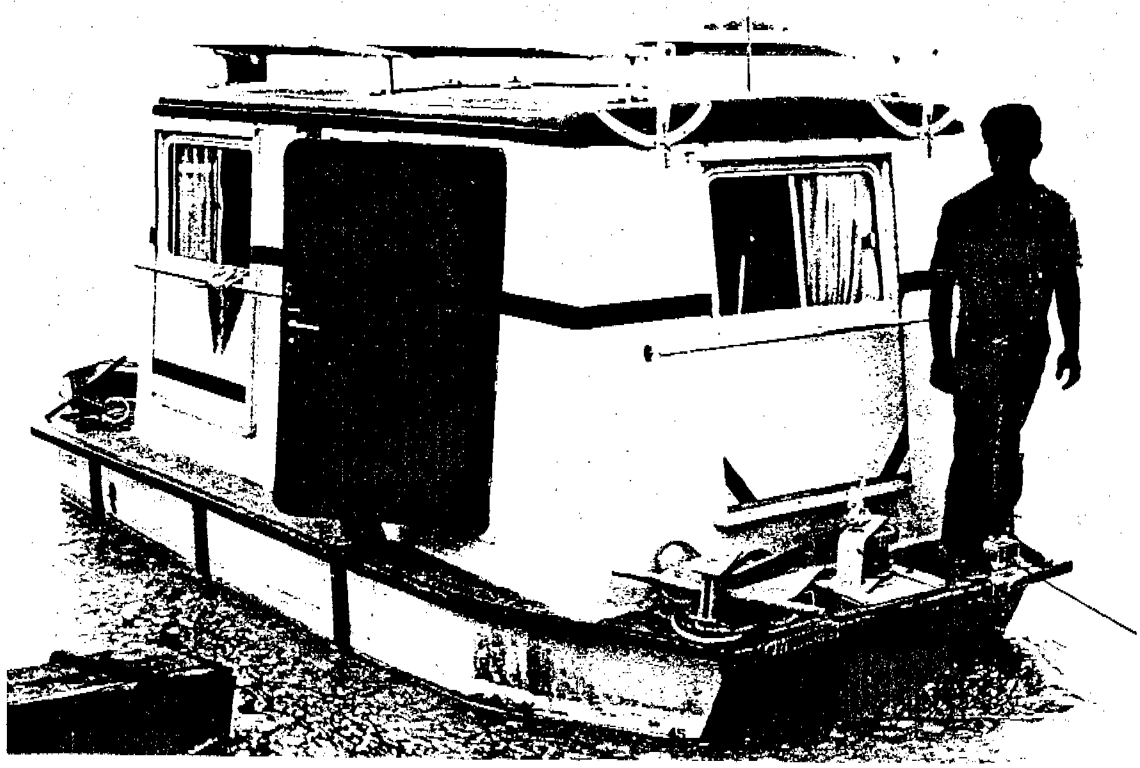
These investigations represent part of a large programme of surveys carried out in 1987 and 1989 in the vicinity of major cities known to contribute significant pollution loads to the Ganges. All survey sites were potential sites for the introduction of ARQM. These were in the vicinity of Allahabad and Kanpur (surveyed in 1987) and Kannauj, Kanpur, Patna and Barauni. Three sites on the Hoogli Estuary near Calcutta were also surveyed in 1989 and as noted above, surveys were carried out at Varanasi in both 1987 and 1989 (Thames Water International, 1987 and 1989).

FIGURE 2
Schematic drawing of river quality monitoring station



Outline of sensor assembly position within floating platform

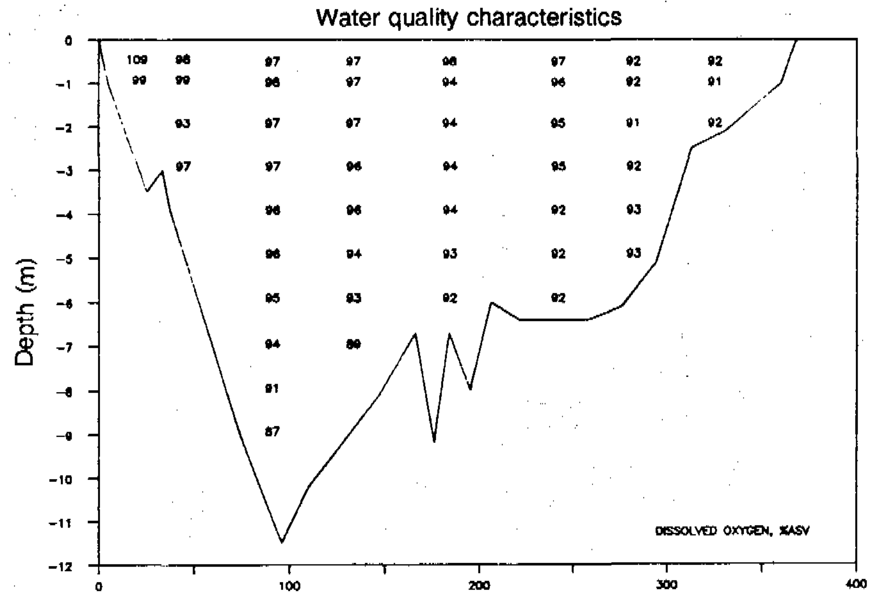
FIGURE 3
River quality monitoring station on River Ganges at Kanpur



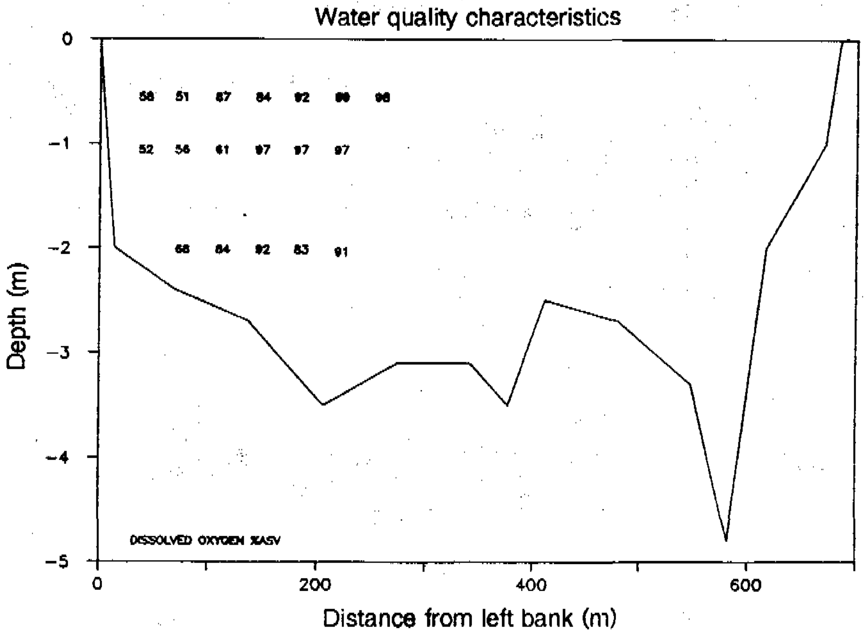
Topographical, physico-chemical and bacteriological surveys were undertaken across transects at strategic points in the vicinity of the cities studied with effort being concentrated upstream and downstream of the major effluents. A series of depth profiles was recorded at selected transect locations, the number of measurements being dependent upon the variability of the river. The depth profiles showed river bottom features identified by echo sounder. At full transect sites profiles of the flood plain were fixed using the electronic distance measurer.

The results of the river surveys at Varanasi are summarised in Figures 4, 5 and 6 which are examples of a cross-sectional dissolved oxygen profile, bacteriological results and a management summary diagram indicating the distribution of pollution in the river.

FIGURE 4
Examples of cross-sectional dissolved oxygen profile of the River Ganges at Varanasi, 1987



Varanasi, Lali Ghat



Varanasi, 100 m d/s Var

FIGURE 5
Bacterial counts: thermo-tolerant coliforms/100 ml, Varanasi, April 1987

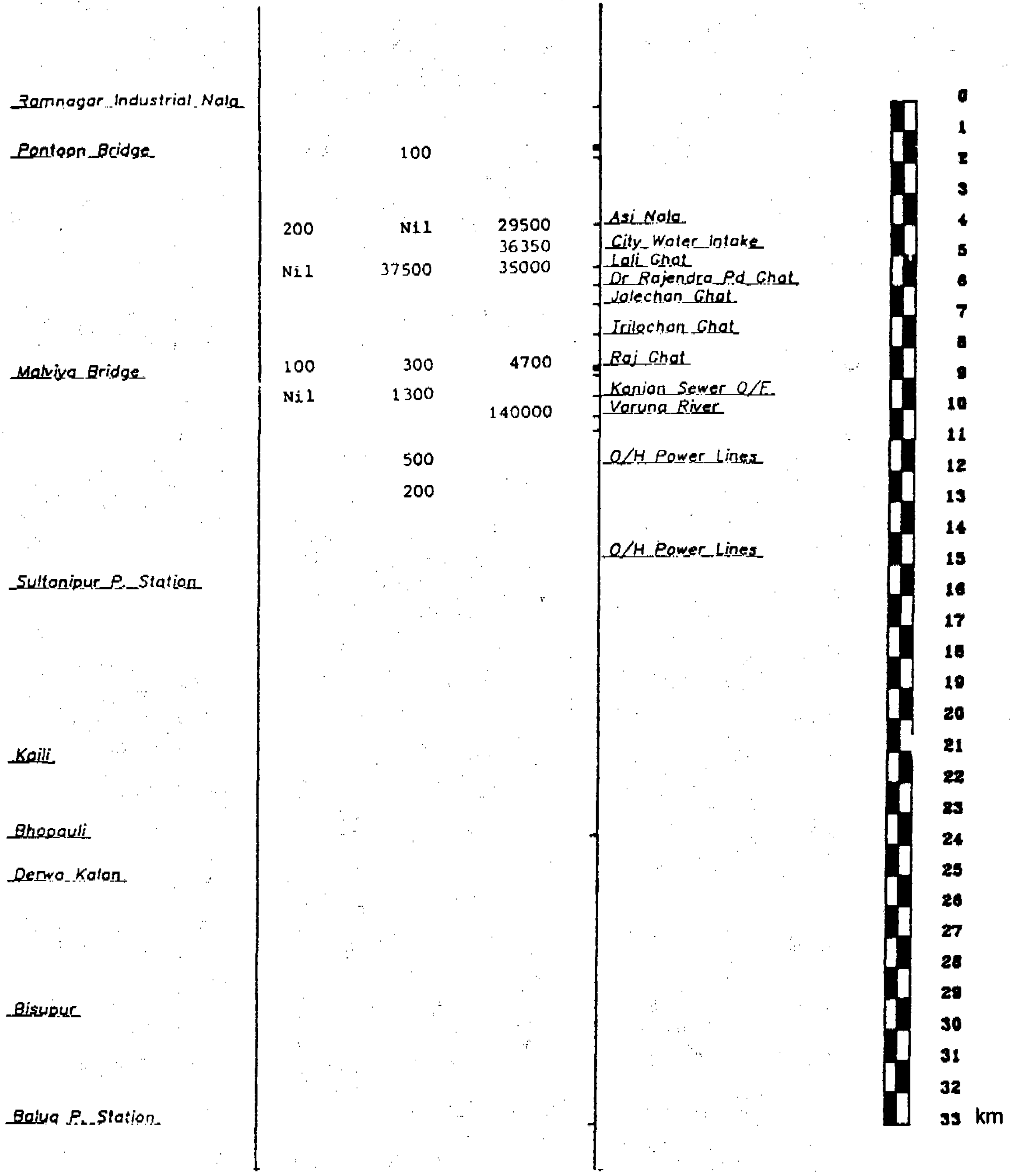
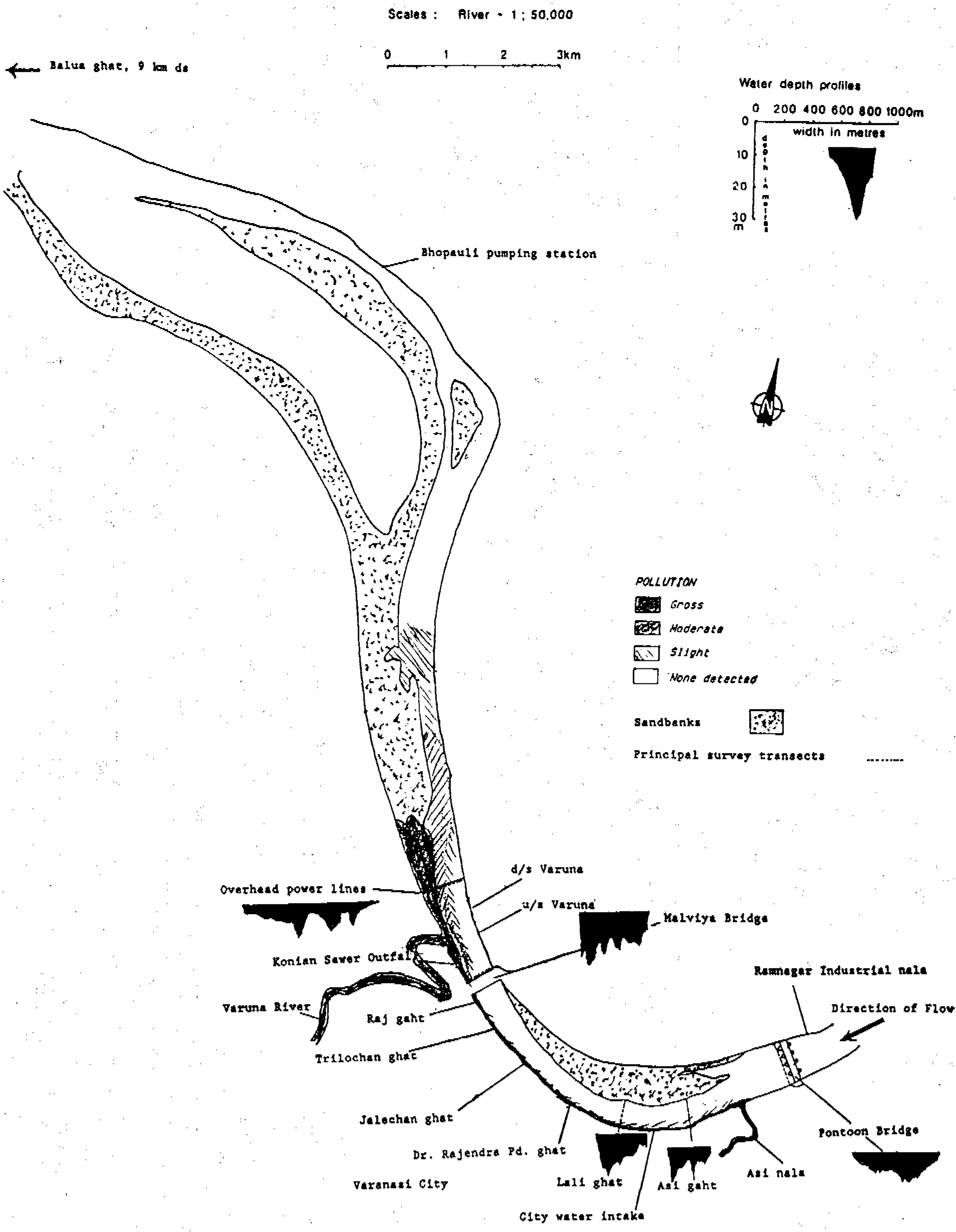


FIGURE 6
Schematic diagram of water depth profiles and pollution streaming: summary of survey findings, Varanasi, 1989



DISCUSSION

Reasons for the use of ARQM on the River Ganges

In order to fulfil the aim of the Ganga Action Plan to improve the water quality status of the River Ganges, it is essential to have comprehensive information on the river's quality on a 24-hour basis. ARQM systems will assist in gathering this information.

ARQM serves to complement the limited laboratory facilities in India and the system specified has an advantage of being based on and adapted from a proven system in operation on the River Thames. The modular design should assist in maintenance and the *in-situ* configuration will allow the ARQM stations to be easily moved to new sites if required.

The survey work involved in locating suitable monitoring sites improved the basic knowledge of the water quality of the river and the Indian team trained during the surveys has continued to undertake detailed surveys at other sites on the Ganges. The survey equipment used was given to the GPD by the Overseas Development Agency.

Implementation of the ARQM system

The contract to manufacture equipment was awarded to Envirotech (India) Ltd following an international tendering exercise according to World Bank rules. The Indian company tendered a competitive price and some advantage was seen by the Indian government in awarding the contract to an indigenous company. Most of the specialist components were from USA or UK. Considerable delays in manufacture ensued and although the company was competent in electronics and process control it had no experience of constructing equipment to operate in the aquatic environment and considerable redesign of the 'wet end' of the ARQM was required before any acceptable reliability was achieved.

A simple modular approach to equipment design and maintenance was taken with a view to achieving as 'appropriate a technology' as possible for the Indian environment. The use of *in-situ* probes and the exclusion of ammonia monitoring assisted in this. The commissioning trials of the equipment seem promising but the reliability of the equipment and the ease of servicing cannot be assessed fully until the system is operational. The use of solar power should enable the equipment to operate at truly remote sites and should be well suited to the Indian climate.

The experience of operating ARQM on floating piers on the tidal Thames was particularly relevant and formed the basis for the design which utilises *in-situ* deployment of the sensors. The harsh environment, including fluctuations in water level, fast current speeds, probability of physical and biological fouling and remote locations meant that the technology developed for the tidal Thames system was applicable. Dissolved oxygen, temperature and conductivity sensors of a similar type to that used on the tideway were supplemented with turbidity and pH, additional factors important to the Indian water quality objective scheme. Measurement ranges were also adjusted to the Indian requirement. Most of the ARQM stations on the tidal Thames are mains powered with the exception of the self-contained floating monitoring station at Crossness. This is solar powered and although considerable scaling down of solar panels and batteries was possible for the subtropical climate, the technology was directly transferable.

Financial and data communications restrictions prevented the immediate installation of telemetered data collection from the Indian stations, although provision was made in the station design to add this at a later date. Dataloggers were installed and earlier experiences in the Thames catchment with their use assisted in the development of working practices, data collection routines and in data storage and presentation.

Finally, assistance in staff training, equipment commissioning and in setting up secure working practices has assisted in the development of ARQM in India.

Water quality of the River Ganges

The programme of surveys provided a considerable amount of information about the water quality status of the Ganges and its tributary the Yamuna (Thames Water International, 1987 and 1989. In general, the water quality of the Ganga and its major tributary, the Yamuna, is able to support a wide diversity of plant and animal species. Its fish and invertebrate communities are exceptional (Jhingran, 1978) and freshwater dolphins, extensive bird populations and reptiles were evident during the survey. High flows and the resultant dilution assist to give great powers of self purification.

Localised areas of gross pollution are associated with major cities where a variety of demands upon the river are made. In these cities the riverside is intensively used for religious bathing, drinking water, disposal of domestic and industrial waste and animal husbandry. It is in the cities and major towns where gross pollution coincides with intensive water use that environmental problems and major public health risks occur.

The major seasonal changes experienced in the subtropical environment must be taken into account when assessing water quality. The surveys were undertaken during the dry season when river flows are at their lowest and temperatures at their highest. The gross pollution from urban areas was expected to have maximum effect at this time. However, the monsoon regime of flow will have a considerable effect upon water quality (Payne, 1986). At the height of the monsoon flows, considerable dilution and river cleansing takes place. This is used by some factory complexes, for example at Barauni where effluents stored in temporary lagoons are flooded away in the monsoon (Mohan, personal communication).

At the onset of the monsoon considerable quantities of silt and other polluting matter are displaced down the river in a short period of time, the 'first flush' effect (Ittekkot *et al.*, 1985). This has been noted on the Yamuna, downstream of Delhi where the river becomes anaerobic during the dry season and sewage sludges settle on the river bed. At the first rains this septic water, sludge and run off from the city sweeps down the river causing gross pollution resulting in major fish kills for tens of kilometres downstream (Trevedi, personal communication). The ARQM may be very important in assessing the effects of this first flush effect. Because the Yamuna has relatively little flow in the dry season the polluting effects on the river downstream are not extensive. Fish populations can recolonise from the unpolluted tributaries once the first flush has passed.

During the post monsoon period, the river flows recede and nutrients are rapidly assimilated by plant and animal activities. During the dry season, the river has the chemical and physical appearance of an oligotrophic environment. However, closer examination of the benthic invertebrate communities shows that high productivity occurs during the post monsoon period (Andrews, personal communication).

The 'oligotrophic' nature of the river in the dry season and the nature of the flora and fauna present make the river very vulnerable to damage from eutrophication. The indigenous fauna and flora are unlikely to withstand a greatly increased pollution load. The river is currently protected by the lack of mains sanitation which, combined with insufficient water resources in the majority of large conurbations, prevents the pollution load from reaching the river. The current pollution loads are a fraction of what might be expected from cities of comparable population in the West. In addition, during the dry season non point source pollution loads to the Ganges are negligible (Payne, 1986).

There are some indications that pollution loads are already increasing. For example at the major industrial city of Kanpur, the river is reaching saturation point and water quality is poor, although it never becomes anaerobic (Thames Water International, 1987). At other sites, the river rapidly recovered from the pollution loads generated at each city which, although causing local pollution problems, never extensively threatened the ecosystem to the same extent as at Kanpur.

The immediate problems at Kanpur may be alleviated in the short term by improving the sewage treatment works (the civil engineering is already underway as part of the Ganga Action plan). However, the overall polluting load on the river must be maintained at a low level and the requirements for effluent standards may have to be extremely strict to maintain the vulnerable riverine community.

There is some evidence to suggest that the fish and reptile community has already been damaged by man's influence and migratory fish populations are impoverished. It was likely that large migratory fish runs occurred. Now only meagre catches of small cyprinid fish are taken from the river (Jhingran, 1978). Unlike the River Thames there is no evidence to suggest that water quality forms a complete barrier, either in the estuary or the freshwater Ganges.

This complex climatic and flow regime requires a totally different pollution control strategy from that used in temperate climates, such as the UK, which is so often applied to the Indian environment. It is hoped that ARQM and associated river quality investigations will provide more information on natural, seasonal or man-made water quality changes, which will act as a basis for the management and formulation of practical solutions to public health, pollution control and environmental protection on the River Ganges.

CONCLUSIONS

River surveys yielded considerable information on the quality of the River Ganges. In general the water quality of the river is good and it is able to support a wide variety of plant and animal species. Localised areas of gross pollution are associated with major cities where a variety of demands on the river are made. Here gross pollution coincides with intensive water use and public health and environmental risks occur.

The river appears vulnerable to extensive damage if pollution loads increase significantly. The river is currently protected by the lack of mains sanitation which, combined with insufficient water resources in the majority of large conurbations, prevents the pollution load from reaching the river. The current pollution loads are a fraction of what might be expected from cities of comparable population in the west. In addition, during the dry season non point source pollution loads to the Ganges are negligible (Payne, 1986). Some evidence of the deleterious effect of increasing pollution loads were noted at Kanpur.

The research and development work undertaken in the River Thames catchment was invaluable for the transfer of the technology to the River Ganges. It enabled a structured approach to be taken to the specification of the system so as to ensure that a reliable and serviceable monitoring system was developed.

The integrated nature of the project enabled a full overview of the pollution control issues to be taken. The water quality data from the survey were fed back into predictive mathematical models enabling the design criteria for the sewage treatment plants to be calculated. Remedial work could be prioritised and short-term solutions have been progressed. These include the resiting of outfalls away from potable abstractions and bathing areas in Varanasi and Allahabad.

Water quality monitoring programmes are now underway on the River Ganges. Three prototype monitors are currently undergoing extended trials. A data archive to collect, interpret and store the data from the ARQM stations and the complementary manual sampling programmes has been developed and is being commissioned. In addition, biological monitoring methods have been developed and are in use.

ACKNOWLEDGEMENTS

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DISCUSSION

The criteria used for improving river water quality was discussed. Criteria were related to intended uses including drinking, sustaining fish and particular to India, for bathing. It was said that there is a tendency for pesticides and other potential effluents to accumulate on the land during the dry season but it is flushed into the river during the first rains of the monsoon. Some industries used lagoons for storage of their effluent and relied on these being flushed out during the monsoon. This was probably an acceptable procedure at present, provided that the waste did not contain a toxic component. It was asked whether the changes in flora and fauna in the Varanasi indicated that the river was more seriously polluted than the paper suggested. Fish stocks were smaller than expected but it was said that this was due primarily to river barrages which have disrupted migration patterns. Lack of data and difficulties of access to that which existed was recognised as a serious problem.

PAPER 8

Wastewater treatment and use for irrigation

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Summary: The paper describes the potential health risks associated with wastewater use for irrigation and identifies helminths as the pathogens of greatest concern. Environmental and agricultural impacts resulting from wastewater irrigation are reviewed and the need for consideration of wastewater quality at the project planning stage is stressed. The new wastewater quality guidelines, introduced by WHO in 1989, are given and attention drawn to the FAO irrigation water quality guidelines applied to wastewater irrigation in the 1992 'Irrigation and Drainage Paper No. 47'. Wastewater treatment, crop selection, application control and human exposure control are discussed as alternative and complementary techniques and strategies for managing treated wastewater use in agriculture. Finally, case-study examples from Jordan, Tunisia, Kuwait and Mexico are used to illustrate some of the strategies.

INTRODUCTION

Wherever a community's wastewater is collected in sewers and irrigation water is scarce, raw wastewater is likely to be used by farmers. In the past, this has often had adverse health impacts, causing international agencies, particularly the World Health (WHO) and Food and Agriculture (FAO) Organizations of the United Nations, to become increasingly concerned. It is recognized that the nutrients contained in domestic wastewater will benefit agriculture, so effluent re-use is to be encouraged. However, unacceptable health and environmental risks cannot be tolerated. Considerable progress has recently been made to assess health and environmental risks associated with wastewater use in irrigation and to develop suitable guidelines.

Land application is often the most economical way to dispose of wastewater and sludge - but municipal sewage carries harmful pathogens and may also contain dangerous levels of heavy metals and industrial organic compounds. Direct use of municipal sewage without pre-treatment and without applying any other controls will lead to serious health risks and possibly to impairment of the soil's long-term productivity. The problem is especially acute in developing countries where restricting raw wastewater use in irrigation has been difficult and resources to invest in costly wastewater treatment are scarce. Low-cost alternatives are necessary if poorer countries are to take advantage of this additional water resource for crop irrigation in an organized and controlled manner.

Wealthier countries have tended to rely on advanced wastewater treatment technology for health and environmental protection. This is not only costly, but conventional secondary and tertiary sewage treatment processes are notoriously difficult to operate and maintain. Experience with such processes has not been good in developing countries and this approach is unlikely to be successful in the near future. Fortunately, alternative control measures to minimize health and environmental risks are available.

HEALTH RISKS ASSOCIATED WITH WASTEWATER USE FOR IRRIGATION

The potential risk of infection being transmitted to plants, animals and humans through land application of wastewater is attributable to the presence of pathogenic organisms in the raw wastewater. Under favourable conditions, enteric pathogens can survive for long periods on crops and in the soil, as indicated in Table 1 from Feachem *et al.* (1983). However, despite the extensive world-wide practice of nightsoil and sewage sludge application and raw wastewater

TABLE 1
Survival of excreted pathogens at 20-30°C

Type of pathogen	Survival time in days In faeces, nightsoil and sludge	In fresh-water and sewage	In the soil	On crops
Viruses				
Enteroviruses	<100 (<20)*	<120 (<50)	<100 (<20)	<60 (<15)
Bacteria				
Faecal coliforms	<90 (<50)	<60 (<30)	<70 (<20)	<30 (<15)
Salmonella spp.	<60 (<30)	<60 (<30)	<70 (<20)	<30 (<15)
Shigella spp.	<30 (<10)	<30 (<10)	-	<10 (<5)
Vibrio cholera	<30 (<5)	<30 (<10)	<20 (<10)	<5 (<2)
Protozoa				
Entamoeba histolytica cysts	<30 (<15)	<30 (<15)	<20 (<10)	<10 (<2)
Helminths				
Ascaris lunbricoides eggs	Many months	Many months	Many months	<60 (<30)

Source: Feachem *et al.*, 1983
* Figures in brackets show the usual survival time

irrigation, few epidemiological studies have definitely established adverse health impacts from consuming food grown in this way.

Those epidemiological studies that have been conducted, as reported by Shuval *et al.* (1984) and Gunnerson *et al.* (1984), have shown that transmission of helminthic infections (*Ascaris and Trichuris spp.*) has been found to occur where these diseases were endemic in the population and where raw untreated wastewater was used to irrigate salad crops and/or other vegetables that are generally eaten raw. Some evidence suggests that cholera has been transmitted through the same channel. Reports from Melbourne, Australia and Denmark, reviewed by Gunnerson *et al.* (1984), confirmed that beef tapeworm (*Taenia saginata*) has been transmitted to people consuming the meat of cattle grazing on wastewater-irrigated fields, or fed crops from such fields. Although the reported incidence of disease transmission to workers on sewage farms has been inconclusive, there is always a potential risk associated with direct contact of wastewater with hands, especially where personal hygiene is not strict. Finally, the inhalation of aerosolized sewage containing pathogens from spray irrigation is a possible mode of disease transmission but no evidence has been presented to confirm this.

The health risks associated with wastewater re-use can show up to different extents in different subgroups of the population. The most important sub-groups to consider are those that consume crops irrigated with the wastewater (consumer risk) and agricultural workers subjected to occupational exposure (occupational risk). It is also important to consider persons of different ages separately, since the risk to children may be different from the risk to adults. The control measures taken depend on whether consumer risk, occupational risk, or both, are to be minimized.

The method of application, the interval between successive applications, and the interval between the last application and harvesting, all affect the likely degree of crop contamination and the environmental dispersion of excreted pathogens. Agricultural crops intended for human consumption pose potential risks to farm workers, those who handle the products and those who consume them. If they are fodder crops, farm workers and those who consume the resulting meat or milk are at potential risk; in the case of industrial products (for example, sugar beet), only farm workers and product handlers are at risk. Where sprinkler irrigation is used, people living near the irrigated fields are potentially at risk from pathogens present in wind-dispersed aerosol droplets.

The greatest risk occurs when crops - such as salad crops - are eaten raw, especially if they are root crops (radishes) or grow close to the soil (lettuces). Pathogen survival times can be greater than the crop growing time, so contamination is highly likely unless the wastewater is treated to a very high standard.

Significant host immunity only occurs with the viral diseases and some bacterial diseases (for example, typhoid). The role of immunity is most noticeable in the case of viral infections, where infection at an early age is very common (even in communities with high standards of personal hygiene). As a result, the adult population is largely immune to the disease, and frequently also to infection.

The relative importance of such potential health risks from wastewater re-use depends on alternative access routes to excreted pathogens, such as lack of safe water supply. If there are no such routes, wastewater re-use will be entirely responsible for the risk induced. However, Shuval *et al.* (1986) have pointed out that negative health effects have only been detected in association with the use of raw or poorly-settled wastewater, while inconclusive evidence has suggested that appropriate wastewater treatment could provide a high level of health protection. In respect of the health impact of wastewater use for irrigation, these workers rank pathogenic agents in the following order of priority of concern:

• **High risk** (high incidence of excess infection)	Helminths (*Ancylostoma, Ascaris, Trichuris* and *Taenia*)
• **Medium risk** (low incidence of excess infection	Enteric bacteria (*Cholera vibrio, Salmonella typhosa, Shigella* and possibly others)
• **Low risk** (low incidence of excess infection)	Enteric viruses

ENVIRONMENTAL AND AGRICULTURAL IMPACTS OF WASTEWATER USE FOR IRRIGATION

Wastewater has an important role to play in water resources management as a substitute for freshwater in irrigation. By releasing freshwater sources for potable water supply and other priority uses, wastewater re-use contributes to water conservation and takes on an economic dimension.

Those pollutants which, if discharged directly to the environment in raw wastewater, would create serious pollution problems (especially organic matter, nitrogen, phosphorus and potassium) serve as nutrients when applied in irrigation water. Studies in many countries have shown that, with proper management, crop yields may increase by irrigating with raw wastewater, as well as with primary and secondary treated effluents. For an irrigation rate of 2 m/year, commonly required in semi-arid areas, typical concentrations of 15 mg/l of total N and 3 mg/l of total P in well-treated sewage (say, after treatment in a properly designed series of stabilization ponds) correspond to annual N and P application rates of 300 and 60 kg/ha, respectively. Such nutrient inputs will reduce or eliminate the need for commercial fertilizers. The organic matter, biological oxygen demand (BOD), added through wastewater irrigation will serve as a soil conditioner over time, increasing the capacity of the soil to store water.

Discharging untreated or partially treated wastewater to the environment can give rise to pollution in surface and ground waters, and on land. Planned re-use of wastewater for irrigation prevents such problems and reduces the resulting damages which, if quantified, can partly offset the costs of the re-use scheme. Also, by substituting wastewater irrigation for groundwater irrigation in those areas where over-use of groundwater resources is causing problems (such as salt water intrusion in coastal areas), additional environmental benefits might result.

Groundwater contamination might arise from using wastewater in irrigation, and from applying sewage sludge to land. Nitrates are a particular problem in many countries; the risk of contaminating groundwater through wastewater irrigation depends on local conditions as well as on the rate of application. Where a deep, homogeneous, unsaturated zone overlies the saturated layer of the aquifer, most pollutants will be removed in the unsaturated layer and there will be a very low risk of contaminating the groundwater. A high-risk situation will arise only where a shallow and/or a highly porous unsaturated zone exists above the aquifer, especially if this zone is fissured.

Municipal wastewater is likely to contain chemical pollutants wherever industrial discharges are allowed into the sewerage system. Of particular concern are those that are toxic to man, plants and aquatic biota. Heavy metals and refractory organics fall into this category. Boron, a constituent of synthetic detergents, is an important phytotoxin, especially of citrus crops, and should be monitored when wastewater is used for irrigation. Preventing chemical pollutants from entering sewerage systems is the best solution but this is difficult to achieve unless industrial zones are isolated and provided with their own wastewater treatment plants.

A possible long-term problem of wastewater irrigation is build-up of toxic materials or salinity in the soil. As the unsaturated zone removes chemical pollutants - particularly heavy metals - their concentration in the soil will increase with time and, after many years of irrigation, it is possible that toxic levels could develop and be absorbed by a crop. Soil salinization is common in arid regions where irrigation water is saline; wastewater irrigation could cause this over the long term, thereby rendering the land unusable for agriculture.

The chronic effects of long-term exposure to low levels of toxic chemicals, through consuming groundwater into which these materials have leached, is also of concern. Although studies have indicated that only negligible amounts of such toxic chemicals normally move 30 cm beyond the point of application within the soil, it is possible that long-term effluent re-use and eventual accumulation of toxic materials in the soil might ultimately lead to their mobilisation and increase groundwater concentrations. Numerous studies have indicated that the content of certain toxic metals in plant tissues is directly proportional to the concentration of such metals within the soil root zone. Thus, long-term application of wastewater in irrigation poses the risk of plants having high levels of toxic materials in their tissues. The FAO 'Irrigation and Drainage Paper No. 29' (Ayers and Westcot, 1985) recommends some maximum concentrations for phytotoxic elements in irrigation water.

WASTEWATER QUALITY GUIDELINES FOR IRRIGATION USE

Health protection measures which can be applied in agricultural use of wastewater include the following, either singly or in combination:

- Wastewater treatment
- Crop restriction
- Control of wastewater application
- Human exposure control and promotion of hygiene.

In the past, wastewater treatment has been widely adopted as the major control measure in controlled effluent use schemes, with crop restriction being used in a few notable cases. A more integrated approach to the planning of wastewater use in agriculture will take advantage of the optimal combination of the health protection measures available and allow for any soil/plant constraints in arriving at an economic system suited to the local socio-cultural and institutional conditions.

A WHO (1989) Technical Report on 'Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture' discusses the integration of the various measures available to achieve effective health protection. Limitations of the administrative or legal systems in some countries will make some of these approaches difficult to apply, whereas shortage of skilled technical staff in other countries will place doubt upon reliance on wastewater treatment as the only control mechanism. To achieve greater flexibility in the use of wastewater application as a health protection measure, irrigation systems must be developed to be capable of delivering low quality wastewater and restrictions on irrigation technique and crops irrigated must become more common.

Many schemes have been proposed for the classification of irrigation water. In the FAO 'Irrigation and Drainage Paper No. 29' (Ayers and Westcot, 1985) irrigation water is classified into three groups, based on its salinity, sodicity, toxicity and miscellaneous hazards, which help to identify potential crop production problems associated with the use of conventional water sources. These guidelines are equally applicable to evaluate wastewaters for irrigation purposes and the recent FAO 'Irrigation and Drainage Paper No. 47' (Pescod, 1992) on 'Wastewater Treatment and Use in Agriculture' adopts the same criteria for chemical constituents, such as dissolved solids, relative sodium content and toxic ions. Such guidelines stress the management needed to use wastewater of a certain quality successfully and must take account of the local conditions at the planning stage of wastewater irrigation schemes.

EFFLUENT QUALITY GUIDELINES FOR HEALTH PROTECTION

The WHO (1989) Technical Report recommended microbiological quality guidelines for wastewater use as irrigation water, as shown in Table 2. These guidelines were based on the consensus view of a WHO Scientific Group of environmental specialists and epidemiologists that the actual risk associated with the use of treated wastewater for irrigation is much lower than previously perceived and that earlier standards and guidelines concerned with health control were unjustifiably restrictive, particularly in respect of faecal coliforms.

The new guidelines are stricter than previous standards in respect of the requirement to reduce the numbers of helminth eggs (*Ascaris and Trichuris* species and hookworms) in effluents for Category A and B conditions to a level of not more than one per litre. Also implied by the guidelines is the expectation that protozoan cysts will be reduced to the same level as helminth eggs. Although no bacterial pathogen limit is imposed for Category C conditions where farm workers are the only exposed population, on the premise that there is little or no evidence indicating a risk to such workers from bacteria, some degree of reduction in bacterial concentration is recommended for any effluent use situation.

The WHO Scientific Group considered the new approach to effluent quality would increase public health protection for the large numbers of people who were now being infected in areas where crops eaten uncooked are being irrigated in an unregulated, and often illegal, manner with raw wastewater. It was felt that the recommended guidelines, if adopted, would achieve this improvement and set targets which are both technologically and economically feasible. However, the need to interpret the guidelines carefully and modify them in the light of local epidemiological, socio-cultural and environmental factors was also pointed out.

The effluent quality guidelines in Table 2 are intended as design goals for wastewater treatment systems, rather than standards requiring routine testing of effluents. Wastewater treatment processes achieving the recommended microbiological quality consistently as a result of their intrinsic design characteristics, rather than by high standards of operational control, are to be preferred. In addition to the microbiological quality requirements of treated effluents used in agriculture, attention must also be given to those quality parameters of importance in respect of groundwater contamination and of soil structure and crop productivity. Although heavy metals may not be a problem with purely domestic sewage effluents, all these elements are potentially present in municipal wastewater.

TABLE 2
Recommended microbiological quality guidelines for wastewater use in agriculture

Category	Re-use condition	Exposed group	Intestinal nematodes[b] (arithmetic mean no. eggs/l[c])	Faecal coliforms (geometric mean no. /100 ml[c])	Wastewater treatment expected to achieve reqd. biological quality
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks[d]	Workers, consumers, public	≤1	≤1000[d]	Series of stabilisation ponds designed to achieve the microbiological quality indicated or equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees	Workers	≤1	No standard recommended	Retention in stabilisation ponds for 8-10 days or equivalent helminth and faecal coliform removal
C	Localised irrigation of crops in Category B if exposure of workers and the public does not occur	None	Not applicable	Not applicable	Pre-treatment as required by the irrigation technology but not less than primary sedimentation

Notes:

[a] In specific cases, local epidemiological, socio-cultural and environmental factors should be taken into account and the guidelines modified accordingly

[b] *Ascaris* and *Trichuris* species and hookworms

[c] During the irrigation period

[d] A more stringent guideline (≤200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact

[e] In the case of fruit trees, irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used

WASTEWATER TREATMENT

The most appropriate wastewater treatment to be applied before effluent use in agriculture is that which will produce an effluent meeting the recommended microbiological and chemical quality guidelines both at low cost and with minimal operational and maintenance requirements. Adopting as low a level of treatment as possible is especially desirable in developing countries, not only from the point of view of cost but also in acknowledgement of the difficulty of operating complex systems reliably. In many locations it will be better to design the re-use system to accept a low grade of effluent rather than to rely on advanced treatment processes producing a reclaimed effluent which continuously meets a stringent quality standard.

Nevertheless, there are locations where a higher-grade effluent will be necessary and it is essential that information on the performance of a wide range of wastewater treatment technology should be available. The design of wastewater treatment plants is usually based on the need to reduce organic and suspended solids loads to limit pollution of the environment. Pathogen removal has very rarely been considered an objective but, for re-use of effluents in agriculture, this must now be of primary concern and processes should be selected and designed accordingly. Treatment to remove wastewater constituents that may be toxic or harmful to crops is technically possible but is not normally economically feasible. Unfortunately, few performance data on wastewater treatment plants in developing countries are available and even then they do not normally include effluent quality parameters of importance in agricultural use.

The FAO 'Irrigation and Drainage Paper No. 47' (Pescod, 1992) deals with wastewater treatment alternatives and stresses the need for reliability of treatment. In the case of developing countries, without experience in operating wastewater treatment plants and short of trained manpower, conventional wastewater treatment processes will be less likely to produce satisfactory effluents consistently than natural low-rate biological treatment systems. Such systems, particularly wastewater stabilization ponds, tend to be lower in cost and less sophisticated in operation and maintenance. Although they tend to be land intensive, they are generally more effective in removing pathogens and do so reliably and continuously if properly designed and not overloaded. Ponds are recommended in the WHO (1989) health guidelines as the preferred method of wastewater treatment for effluent use in irrigation.

STRATEGIES FOR MANAGING TREATED WASTEWATER USE IN AGRICULTURE

Success in using treated wastewater for crop production will largely depend on adopting appropriate strategies aimed at optimizing crop yields and quality, maintaining soil productivity and safeguarding the environment. Several alternatives are available and a combination of these alternatives will offer an optimum solution for a given set of conditions. The user should have prior information on effluent supply and its quality to ensure the formulation and adoption of an appropriate on-farm management strategy.

Basically, the components of an on-farm strategy in using treated wastewater will consist of a combination of:

- crop selection
- selection of irrigation method
- adoption of appropriate management practices.

Furthermore, when the farmer has additional sources of water supply, such as a limited amount of normal irrigation water, he will then have an option to use both the effluent and the conventional source of water in two ways, namely:

- by blending conventional water with treated effluent
- using the two sources in rotation.

Crop selection provides the opportunity to overcome salinity hazards, toxicity hazards and health hazards and details of each aspect are provided in the FAO 'Irrigation and Drainage Paper No. 47' (Pescod, 1992). However, in terms of health control, although crop restriction protects the consuming public it does not protect farm workers and their families. Therefore, it is not adequate on its own and should be complemented by other measures, such as partial wastewater treatment, controlled wastewater application and/or human exposure control. Crop restriction is feasible under the following conditions :

- where a law-abiding society or strong law enforcement exists
- where a public body controls waste allocation
- where an irrigation project has strong central management
- where there is adequate demand for the crops allowed under crop restriction - and they fetch a reasonable price
- where there is little market pressure in favour of excluded crops, such as those in Category C.

Adopting crop restriction to protect health in re-use schemes will require a strong institutional framework and capacity to monitor and enforce regulations. Farmers must be advised why such crop restriction is necessary and be assisted in developing a balanced mix of crops to use fully the constant production of partially treated wastewater. National agricultural planning should take the crop production potential of restricted re-use schemes into account so that production excesses are avoided.

Wastewater application control could, theoretically, allow a raw wastewater to be used for irrigation but, in practice, this would require the development of irrigation systems to deliver low-grade effluent through subsurface systems. Flooding irrigation involves the least investment, but probably exposes field workers to the greatest risk. If the effluent is not of the quality required for Category B, sprinkler irrigation should not be used, except for pasture or fodder crops, and border irrigation should not be used for vegetables. Subsurface or localized irrigation can give the greatest degree of health protection, as well as using water more efficiently and often producing higher yields. However, it is expensive, and a high degree of reliable treatment is required to prevent the small holes (emitters) through which water is slowly released into the soil from clogging. Bubbler irrigation, a technique developed for localized irrigation of tree crops, avoids the need for small emitter apertures to regulate the flow to each tree.

HUMAN EXPOSURE CONTROL

Four groups of people can be identified as being at potential risk from the agricultural use of wastewater:

- agricultural field workers and their families
- crop handlers
- consumers (of crops, meat and milk)
- those living near the affected fields.

Agricultural field workers' exposure to hookworm infection can be reduced by in-field use of appropriate footwear. Immunization is not feasible against helminthic infections, nor against most diarrhoeal diseases, but immunization of highly exposed groups against typhoid and hepatitis A may be worth considering. Additional protection may be afforded by providing adequate medical facilities to treat diarrhoeal diseases, and by regular chemotherapeutic control of intense nematode infections in children and control of anaemia. Chemotherapy and immunization cannot be considered totally adequate, but could be beneficial as temporary palliative measures. Tapeworm transmission can be controlled by meat inspection.

Risks to consumers can be reduced by thorough cooking and by high standards of hygiene. Food hygiene is a theme to be included in health education campaigns. Local residents should be kept fully informed about the location of all fields where wastewaters are used, so that they can avoid entering them and also prevent their children from doing so. There is no evidence that those living near wastewater-irrigated fields are at significant risk from sprinkler irrigation schemes. However, sprinklers should not be used within 50-100 m of houses or roads.

CASE-STUDY EXAMPLES

Wastewater treatment in stabilization ponds: Al Samra, Jordan

The Al Samra Wastewater Stabilization Pond (WSP) System was commissioned in May 1985 and by 1986 was receiving approximately 57 000 m^3/day of domestic wastewater and septage from the Metropolitan Area of Greater Amman, Jordan. This system comprises three trains of ponds, each designed to contain two anaerobic ponds (A-1 and A-2), four facultative ponds (F-1, F-2, F-3 and F-4) and four maturation ponds (M-1, M-2, M-3 and M-4). However, due to the high organic loading on the ponds, in practice the first eight ponds in each train are anaerobic and only the final two behave as facultative ponds.

The performance of the Al Samra stabilization ponds is influenced by temperature, with an average water temperature of 15°C in the cold season (December-March) and 24°C in the hot season (August-November). In terms of overall performance in 1986, the Al Samra ponds were highly efficient, removing 80% and 91% of the incoming BOD_5 on the basis of unfiltered and filtered final effluent samples, respectively. This was the situation with only two trains of ponds in operation when the design organic loading was being exceeded by 57% and the hydraulic loading was 25% greater than design. At the same time, a 4.6 log reduction in faecal coliforms was achieved in passage through the ponds (Al-Salem, 1987).

The microbiological performance of the Al Samra ponds has been described in more detail for the period December 1986 to March 1987 by Saqqar and Pescod (1990). Table 3 shows total coliform and faecal coliform reductions through the pond series for the period concerned. It is clear that the final effluent (after Pond M-4) did not meet the WHO (1989) guidelines figure of <1000 faecal coliforms/100 ml for most of the study period, in spite of having passed through the series of ponds with a minimum theoretical retention time of 34 days. Linear regression analysis of the data indicated that retention time, pond BOD_5 concentration, pH and depth had a significant effect on faecal coliform die-off. Data on nematode egg removal during January and February 1987 showed that nematode eggs were absent from the final effluent (Pond M-4 outlet) over the period and indicated that the WHO (1989) guidelines value of <1/litre could be achieved with the theoretical retention time of 34 days, but not after 24.7 days (Pond F-4 outlet).

TABLE 3
Monthly geometric means for total and faecal coliforms (number per 100 ml)

Month	December 1986		January 1987		February 1987		March 1987	
Average monthly water temp. °C	12.1		11.8		14.9		15.1	
Monthly geometric mean	Coliforms Total	Faecal	Coliforms Total	Faecal	Coliforms Total	Faecal	Coliforms Total	Faecal
Effluent of:								
Pond A1	6.5x10^{7}	2.22x10^{7}	9.59x10^{7}	1.5x10^{7}	9.42x10^{7}	1.90x10^{7}	7.52x10^{7}	1.78x10^{7}
Pond A2	2.59x10^{6}	9.20x10^{5}	4.28x10^{7}	6.18x10^{6}	5.57x10^{7}	1.0x10^{7}	3.23x10^{7}	7.94x10^{6}
Pond F2	4.02x10^{6}	4.73x10^{5}	7.15x10^{6}	1.02x10^{6}	7.05x10^{6}	9.98x10^{5}	6.94x10^{6}	7.84x10^{5}
Pond F4	6.38x10^{5}	6.53x10^{4}	1.24x10^{6}	1.76x10^{5}	8.78x10^{5}	1.12x10^{5}	6.30x10^{5}	9.65x10^{4}
Pond M2	8.21x10^{4}	18180	2.36x10^{5}	31 020	1.28x10^{5}	17 252	4.87x10^{4}	13 924
Pond M4	12 289	1022	27 838	4423	13 161	2631	3908	814

Wastewater treatment and crop restriction: Tunisia

Wastewater use in agriculture has been practised for several decades in Tunisia and is now an integral part of the national water resources strategy. Use of treated effluents is seasonal (spring and summer) and the effluent is often mixed with groundwater before being applied to irrigate citrus and olive trees, forage crops, cotton, golf courses and hotel lawns. Irrigation with wastewater of vegetables that might be consumed raw is prohibited by the National Water Law (Code des Eaux). A regional Department for Agricultural Development (CRDA) supervises all irrigation water distribution systems and enforces the Water Code. At the present time, an area of about 1750 ha is being irrigated with treated wastewater. The La Cherguia activated sludge plant receives sewage from part of the Tunis metropolitan area and discharges its effluent to the La Soukra irrigation area 8 km away. Many new projects are now being implemented or planned and the wastewater irrigated area will be increased to 6700 ha, allowing 95% of the treated wastewater to be used in agriculture. The most important developments will take place around Tunis, where 60% of the country's wastewater is produced and 68% of the effluent-irrigated area will occur.

In the period 1981-87, the Ministries of Agriculture and Public Health, with assistance from the United Nations Development Programme (UNDP), carried out studies designed to assess the effects of using treated wastewater and dried, digested sewage sludge on crop productivity and on the hygienic quality of crops and soil. Treated wastewaters and dried, digested sludge from the La Cherguia (Tunis) and Nabeul (SE4) activated sludge plants were used in the studies and irrigation with groundwater was used as a control. At La Soukra, tests were conducted on sorghum (*Sorghum vulgare*) and pepper (*Capsicum annum*) using flood irrigation and furrow irrigation, respectively. Clementine and orange trees were irrigated at Oued Souhil (Nabeul). In order to assess the long-term effects of irrigation with treated wastewater, investigations were carried out on the perimeter area of La Soukra, where irrigation with treated effluent had been practised for more than 20 years.

The programme of studies not only produced useful results but was also valuable from the point of view of the training of specialists and technicians (Bahri, 1988). The effluent contains moderate to high salinity but presents no alkalization risk and trace element concentrations are below toxicity thresholds. The sewage sludge from Soukra and Nabeul had a fertilizing potential, due to the presence of minerals and organic matter, but was of variable consistency. Evaluation of the fertilizing value of the effluent in relation to crop uptake suggests that the mean summer irrigation volume of 6000 m^3/ha would provide an excess of nitrogen (N) and potassium (as K_2O) but a deficit of phosphorus (as P_2O_5). The fertilizing value of 30 tonnes dry weight of sewage sludge per hectare would be an excess of N and P_2O_5 and a deficit of K_2O. Application of treated effluent and sludge would balance the fertilizing elements but would provide an excess over crop requirements. Excess nitrogen would be of concern from the point of view of crop growth and in relation to groundwater pollution.

Application of treated wastewaters and sewage sludge at the La Soukra and Oued Souhil experimental stations, where the soils are alluvial and sandy-clayey to sandy, has not adversely affected the physical or bacterial quality of the soils. However, the chemical quality of the soils changed considerably, with an increase in electrical conductivity and a transformation of the geochemical characteristics of the soil solution from bicarbonate-calcium to chloride-sulphate-sodium (Bahri, 1988). Trace elements concentrated in the surface layer of soil, particularly zinc (Zn), lead (Pb) and copper (Cu), but did not increase to phytotoxic levels in the short term of the study period. Rational use of sewage sludge would require standards to be developed for the specific soils, based on limiting concentrations of trace elements.

The use of treated wastewater resulted in annual and perennial crop yields higher than yields produced by groundwater irrigation. Sewage sludge application increased the production of sorghum and pepper and resulted in the crops containing higher concentrations of N, P and K and some minor elements (Fe, Zn and Cu). Bacterial contamination of citrus fruit picked from the ground irrigated with treated wastewater or fertilized with sewage sludge was significantly higher than the level of contamination of fruit picked from the trees. Natural bacterial die-off on sorghum plants was more rapid in summer than in autumn. Tests on pepper did not indicate particular contamination of the fruit.

Irrigation with treated wastewaters was not found to have an adverse effect on the chemical and bacteriological quality of shallow groundwater, although the initial contamination of wells was relatively high and subject to seasonal variation. Investigations on the peripheral area of La Soukra did not indicate significant impacts on soils, crops or groundwaters.

Wastewater treatment and human exposure control: Kuwait

Untreated sewage has been used for many years to irrigate forestry projects far from the inhabited areas of Kuwait. Effluent from the Giwan secondary sewage treatment plant was used to irrigate plantations on an experimental farm from 1956 (Agricultural Affairs and Fish Resources Authority, Kuwait, 1988). Following extensive studies by health and scientific committees within the country and by international consultants and organizations (WHO and FAO), the government of Kuwait decided to proceed with a programme of sewage treatment and effluent use. In all, by 1987, four sewage treatment plants were in operation: the 150 000 m^3/day Ardiyah sewage treatment plant (secondary stage) was commissioned in 1971, the

96 000 m^3/day coastal villages and the 65 000 m^3/day Jahra sewage treatment plants were commissioned in 1984 and a small (10 000 m^3/day) stabilization ponds treatment plant had also been installed on Failaka Island. The effluent from the Ardiyah, coastal villages and Jahra, activated sludge treatment plants was upgraded in the middle 1980s by the provision of tertiary treatment, consisting of chlorination, rapid gravity sand filtration and final chlorination.

Initially, the treated secondary effluent from the Ardiyah plant was distributed to the experimental farm of the Department of Agriculture at Omariyah. Trials were undertaken in the early 1970s to compare crop yields from irrigation with potable water, brackish water and treated effluent. An 850 ha farm was established in 1975 by the United Agricultural Production Company (UAPC), under Government licence, especially for the purpose of utilizing the treated wastewater. The directors of this close shareholding company represented the main private organizations involved in Kuwait agriculture, in particular the local dairy, poultry and livestock farming organization. In 1975, only part of the area was under cultivation, with forage (alfalfa) for the dairy industry the main crop, using side-roll sprinkler irrigation. However, aubergines, peppers, onions and other crops were grown on an experimental basis, using semi-portable sprinklers and flood and furrow irrigation.

The Government strategy for implementation of the Effluent Utilization Project was to give the highest priority to development of irrigated agriculture by intensive cultivation in enclosed farm complexes, together with environmental forestry in large areas of low-density, low water-demand tree plantations. By 1976, however, the total cropped area in Kuwait was only 732 ha and the country relied heavily on food imports and imports of both fresh and dried alfalfa were considered to be unnecessarily high. In late 1977, the Ministry of Public Works initiated the preparation of a Master Plan for effective use of all treated effluent in Kuwait, covering the period up to the year 2010 (Cobham and Johnson, 1988).

Construction of works for effluent utilization according to the Master Plan began in mid-1981 but delays in the provision of permanent power supplies to all 12 sites deferred commissioning of the project until 1985. A data-monitoring centre receiving treated effluent from Ardiyah and Jahra has been provided and includes two 170 000 m^3 storage tanks, pumping station, administration building incorporating laboratories for monitoring effluents and soils and workshops for maintenance and stores. In 1985, the treated effluent supplied to the experimental farm and irrigation project was used to irrigate the following:

- Fodder plants - alfalfa, elephant grass, Sudan grass, field corn (maize), vetch, barley, etc.
- Field crops - field corn (maize), barley, wheat and oats
- Fruit trees - date palms, olive, zyziphus and early salt-tolerant vines (sprinklers were not used for fruit trees)
- Vegetables - potatoes, dry onions, garlic, beet and turnip were irrigated by any method; vegetables which are to be cooked before consumption, such as egg plant, squash, pumpkin, cabbage, cauliflower, sweetcorn, broad beans, Jews mallow, Swiss chard, etc., were irrigated in any way but not by sprinkler; vegetables which are eaten raw, such as tomatoes, water melons and other melons, were irrigated with tertiary-treated sewage effluent by drip irrigation with soil mulching.

The yield of green alfalfa was 100 tonnes/ha/year and the total production from the agricultural irrigation project, using primarily treated sewage effluent, was 34 000 tonnes of vegetables and green fodder plants, including dehydrated alfalfa and barley straw. At this production level, a reasonable supply of some vegetables was made available to the local market, the total demand for green alfalfa for animals was satisfied and some of the needs for dehydrated fodder were met.

In Kuwait, the decision was taken to exclude all amenity uses for the treated effluent and to restrict agricultural use to safe crops. Furthermore, areas of tree and shrub planting and the agricultural farm were to be fenced to prevent access. An efficient monitoring system for the treated effluent, the soil and the crops has been implemented since the experimental farm was initiated. The guidelines for tertiary-treated effluent quality used in irrigation are:

- Suspended solids - 10 mg/l
- BOD$_5$ - 10 mg/l
- COD - 49 mg/l
- Cl$_2$ residual - about 1 mg/l after 12 hours at 20°C
- Coliform bacteria - 10 000/100 ml for forestry, fodder and crops not eaten raw
  - 100/100 ml for crops eaten raw.

Even the tertiary-treated effluent meeting these guidelines is not to be used to irrigate salad greens or strawberries. Cadmium was the only heavy metal of concern and special attention was given to monitoring the effluent and crops for this element and to measuring Cd in the kidneys of animals fed on forage irrigated with treated sewage effluent. Agricultural workers dealing with sewage effluent are medically controlled as a pre-employment measure and given periodic (six-monthly) examinations and vaccinations. No outbreaks of infectious disease have occurred since this procedure began in 1976. The impact of treated effluent irrigated vegetables on the consumer has not been possible to assess because no segregation of vegetables produced in this way is effected in the market.

Crop restriction for wastewater irrigation: Mexico

Use of raw sewage for irrigation in the Mezquital Valley of the Tula River Basin began in 1886 (Sanchez Duron, 1988). However, it was not until 1945 that the Ministry of Agriculture and Water Resources established the Number 03 Mezquital Irrigation District to manage the distribution of wastewater from Mexico City for irrigation purposes. Irrigation is essential in this Irrigation District because rainfall is limited and poorly distributed over the year, most falling between July and September. Sewage from Mexico City mixed with variable proportions of surface water collected in reservoirs within the basin has enabled farmers in the Mezquital Valley to provide agricultural produce for the capital city. At different times and places in the District, the following types of irrigation water might be used separately or in combination:

- River water - containing little or no contamination from urban wastewater

- Impounded river water - diverted from reservoirs, or river reaches downstream receiving spillway overflows, containing wastewater discharged into the reservoirs from the main collector canals

- Wastewater - from the main collector canals, composed of sewage and urban storm runoff.

Hence, the concentrations of chemical constituents and pathogenic organisms in the irrigation water will vary spatially and temporally. Large impounding reservoirs (such as Endho) providing relatively long retention times for wastewater will serve as treatment devices, settling out solids and reducing pathogen levels. Nevertheless, in general, faecal coliform levels in the irrigation water are 10^6-10^8/100 ml.

No treatment of sewage is provided before it is transported the 60 kilometres from Mexico City to Irrigation District 03 and, clearly, little improvement in faecal coliform levels has occurred before it is applied as irrigation water. In trying to achieve public health protection, reliance is placed on the application of crop restrictions rather than wastewater treatment. Every year, each farmer specifies the crops he is going to plant and irrigate with water allocated by the Irrigation District. The Ministry of Health sets the basic rules for crop restriction and the District's directing committee specifies in detail the crops which may not be cultivated under its jurisdiction (Strauss and Blumenthal, 1989). In Irrigation District 03, banned crops are: lettuce, cabbage, beet, coriander, radish, carrot, spinach and parsley. Adherence to these restrictions is monitored mainly by the District's canal and gate operators, who are in close contact with farmers. Maize, beans, chili and green tomatoes, which form the staple food for the majority of the population, do not fall under these restrictions and neither does alfalfa, an important fodder crop in the area.

During the agricultural year 1983/84, 52 175 ha in Irrigation District 03 were harvested to produce 2 226 599 tonnes of food crops, with a value of more than US$ 33 million. The yields of the crops were greater than those obtained 10 years before, except for pasture, and it is believed that fertility conditions, measured on the basis of productivity, are better than before. In addition, it is thought that the high content of organic matter and plant nutrients in the wastewater have improved the physical and chemical properties of the shallow soils in the District. The high rate of application of irrigation water has increased soil organic matter and systematically leached the soils, preventing the accumulation of soluble salts (Sanchez Duron, 1988).

Mexican experience with raw wastewater irrigation suggests that successful enforcement of crop restriction has provided health protection for the general public, including crop consumers. Past studies on the health impact of the use of raw wastewater in agriculture in the Mezquital Valley have shown no consistent significant excess prevalence of gastrointestinal complaints or protozoan (apart from amoebiasis) or helminthic infections in children from communities irrigating with wastewater compared with children from a control community using clean water for irrigation. A study on the health effect of the use of wastewater on agricultural workers in Guadalajara concluded that a high prevalence of parasitic diseases in both exposed and control group workers was due to poor environmental sanitation, poor hygienic habits and lack of health education. However, a significant excess prevalence of infection in the exposed group was found for *Giardia lamblia* (17% in exposed versus 4% in control group) and *Ascaris lumbricoides* (50% in exposed versus 16% in control group). This led Strauss and Blumenthal (1989) to recommend further epidemiological studies on the increased health risk to farm workers and at least partial treatment of wastewater, to remove helminth eggs and protozoan cysts, in future wastewater use schemes in Mexico.

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DISCUSSION

There were a number of questions posed over the problems and risks associated with the use of wastewater for irrigation. It was said that there was a risk of contaminating crops from sub-surface delivery of wastewater only in the case of root crops. Salinity was not necessarily a problem. Heavy metals do not generally present a problem in urban wastewater in developing countries but where they did exist in significant quantities they would have to be dealt with. The tight WHO standard for *Ascaris* eggs was difficult to measure and further work was being done on developing techniques. Helminths would survive for one month but the use of a settling pond could be an efficient way in which to deal with them, although this leads to the question of how to use the sediment. On the potential for using wastewater in aquaculture the WHO 'Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture' was referred to.

PAPER 9

Institutional aspects of watershed management

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Summary: The focus of this paper is on the management of upland watersheds. Although conceptually a powerful case can be made for using watersheds as the basis for development planning within a region, the historic dominance of downstream interests has contributed to the neglect of upland development; and it is only recently that heightened concerns about poverty and the environment have encouraged the emergence of new approaches to the development and management of these complex, diverse and risk-prone areas. Evidence from recent experience in Africa and South Asia suggests that, both in contexts where large downstream projects such as hydro-electric schemes provide scope for revenue to be reinvested upstream and where there are no such opportunities, the only approach to development that is likely to achieve success is one that seeks to build from the bottom up. Active farmer participation in the planning and development process is essential, and this is most likely to be elicited where quickly realisable benefits can be obtained from water conservation. Choice of appropriate technologies and institutions will vary substantially, according to the physical and socio-economic characteristics of each locality. The paper concludes with some general propositions and a brief outline of some of the elements that might be needed to form a successful strategy for future development in this difficult field.

INTRODUCTION

'Watershed management' can mean many different things to different people. Perspectives may vary greatly, depending on a person's disciplinary background and field experience. Any attempt to generalise about the subject must therefore be prefaced by some discussion of definitions and subject-matter boundaries and by a statement of limitations and possible biases in the author's perceptions.

Even on its own, the word 'watershed' can be a source of confusion. It is used here in its American sense, as a synonym for what has been more commonly known in Britain as a 'catchment' - a usage that requires the traditional British watershed to be referred to as a 'watershed boundary'. Many may regret the change, but this is the terminology now most generally accepted internationally. When 'management' is added, we find that the term embraces a large number of possible themes and sub-themes. These are the product of different permutations of several factors, of which the most important are:

- The physical unit to be managed, which can vary greatly in terms of:
    - scale, from very large (whole drainage or river basin) to very small (micro-watersheds of as little as 500 ha)
    - location (the whole basin, or only its upper or lower sections)
- The nature of the management task, which can range from water resources planning (usually at the level of the whole river basin or in its lower, downstream section) to the implementation of development activities involving the combined management of water, land and other resources (often within upper watershed areas only).

The themes of large-scale water resources policy and planning and of downstream water management are quite extensively addressed in other conference papers. This paper will therefore focus primarily on issues relating to the management of upland watersheds: "the area of land contained within a drainage divide above a certain specified point on a stream" (Doollette and Magrath, 1990) - a point often determined in practice by engineering works that control and divert surface water for downstream uses, including major irrigation or hydro-electric schemes. In this sense of the term, watershed management is often understood to mean an approach to managing agriculture in predominantly rainfed upland areas, in deliberate contradistinction to the management of irrigated lowland agriculture.

In the discussion that follows, it should be borne in mind that this author's direct perceptions and experiences of watershed management issues have been largely derived from South Asia. Though the paper attempts to balance this through references to experience elsewhere, many of its generalisations and hypotheses are unlikely to be valid universally and should be regarded as very much open to further modification and correction in the light of other regions' physical, demographic, social, economic and political conditions. This is a subject that has yet to be studied systematically across countries and regions. In the absence of such work, this is inevitably a preliminary and partial foray into seriously under-explored territory.

THE LARGER CONTEXT: UPSTREAM-DOWNSTREAM RELATIONSHIPS

As an entry into discussing the theme of upland watershed management, it is important to understand the larger context in which any programme or project action designed to promote such management is likely to be embedded. Conceptually, a powerful case can be made for using watersheds, in their largest sense as drainage basins, to provide the basic framework for development planning within a region; and for advocating the creation of institutions that will moderate between the interests of upstream and downstream users. Thus it has been argued that:

> "where the land/water/climate/people interaction is a major focus for development (i.e. land and water use) this interaction is most strongly expressed in a watershed. Moreover, water seems increasingly to be the key physical resource limiting or triggering economic development in rural areas. The success or failure of a plan can lie in choosing a boundary which is relevant to the principal planning issues, covers sufficient natural and social linkages to operate as a functional unit, and allows effective plan implementation ... The watershed unit not only integrates natural systems, but also many social processes and patterns as well ... " (Hamilton and King, 1984).

The same authors go on to observe that "ecosystem processes ... provide compelling reasons for using the drainage basin as an integrating planning unit". With respect to social processes, they see the need for integrated planning as equally compelling, while recognizing that "in many developing countries ... occupational, social, or ethnic differences between highlanders and lowlanders, hill tribes and valley tribes, upstream residents and downstream residents" tend to lead to conflict. While at the micro- or meso- (e.g. small upland valley) level, these differences may help to create a sense of local solidarity, there is usually a strong "polarization of interest and values between upstream and downstream inhabitants". At this macro- (drainage basin) level, the authors envisage a planning process, the institutions of which are not specified, that will recognize the likely existence of conflict, "with upstream residents often perceiving themselves as bearing the brunt of the costs to the benefit of the downstream people"; and will then seek to "internalize" the problem by introducing "some system of trade-off or compensation".

This conceptual framework could be further elaborated to posit a hierarchy of institutions with responsibilities for rural development (or natural resources) planning and management, from micro-watershed/village level, through watershed/district level, to drainage basin/regional level. However, in practice, despite the framework's inherent attractiveness and logical appeal, the prevalent institutions in most developing countries bear little or no resemblance to it. Instead, their agencies of government tend to be organised on vertical, sectoral lines, with all departments, other than those concerned with large-scale surface irrigation, operating within non-hydrological boundaries; and, because historically the early priorities for water development have nearly always lain downstream, it serves the interests of the more politically powerful downstream users to retain the original institutions set up for the purpose rather than agree to their replacement by something that would be much more 'rational' and equitable from an ideal resource optimising viewpoint. In other words, the shape of water related planning and management institutions has so far been much more influenced by *realpolitik* (implicit in Hamilton and King's reference to the "polarization" of upstream /downstream interests) than by objective considerations of hydrological rationality.

Thus, in the formative stages of large-scale water development, where the principal objectives are to provide irrigation, flood control and/or hydroelectric power to downstream users, the leading government agencies concerned have tended to see the management of upstream watersheds as having the primary, if not sole, purpose of improving downstream sedimentation and runoff regimes. In such a perception, those watersheds are physical entities to be 'treated' through various technical interventions, such as tree-planting and soil conservation. To the extent that they are also perceived to be populated, the conventional agency view has been that the environment should be protected from degradation by the local people through enforced forest and soil conservation measures. Meanwhile, upland areas unadjacent to major water projects have been seen as low priority, low potential areas (unless well forested) and have experienced institutional neglect, with at best thin and fragmented coverage by many different line agencies.

To begin to reverse this process over time and give the upstream areas even a vestige of the bargaining power that Hamilton and King envisage, two conditions are necessary: increasing pressure of demand for the total water resources of a river basin; and the emergence of political (often allied to financial) pressures for institutional reform. In many parts of South Asia, which has a long history of water resources development, the first condition clearly applies; yet attempts in India to promote a National Water Policy on the basis of river basin planning continues to be effectively stalled by a powerful nexus of people whose interests are best served by the continuing dominance of decision-making by Irrigation Departments in charge of heavily subsidised, construction-oriented surface water projects. Similarly in Bangladesh an excellently conceived Master Water Plan has been supplanted by a Flood Action Plan that gives primacy to large surface water control measures. So long as such conditions prevail, upland areas will remain at a severe disadvantage (Bottrall, 1992).

THE NEW INTEREST IN UPLAND DEVELOPMENT

The degree of downstream bias in much of South Asia may be extreme, but it is illustrative of a broader general tendency. Nevertheless, recent years have seen a marked swing of the pendulum, especially among donor agencies, towards greater investment in previously neglected upland areas. This has been accompanied by a new concern to develop alternative approaches to the management of upland areas that would benefit the very large number of poor and disadvantaged people living there *as well as* those living downstream (Romm, 1981). Principal reasons for the change include rapidly increasing population densities in fragile upland environments; the persistent failure of enforced conservation; and the growing difficulty of finding economically attractive large water projects without major social and environmental costs.

In some cases, where upstream/downstream conflicts have become particularly acute (as e.g. between drought-affected uplanders and sugar-cane-irrigating lowlanders in Maharashtra; or between tribal 'oustees' and proposed lowland beneficiaries of the Narmada dams), a still more radical position has been taken by environmental and other groups in support of action that would benefit the former *instead of* (or even *at the expense of*) the latter. But most of the new initiatives are not being designed, at least overtly, as a direct challenge to downstream interests.

These new concerns have brought with them a wide range of suggested strategies for improving the conditions and livelihoods of poor upland farming communities through better resource management. Many of these strategies have been 'sectorally' conceived, in that they are designed to be undertaken through programmes directed by leading line department agencies. They include programmes of rainfed (or dryland) agricultural development, often using a farming systems research and extension (FSR/E) approach; social or community forestry programmes on government-owned land; farm forestry or agroforestry programmes on private land; and small-scale (surface and groundwater-based) irrigation development. Such programmes, although geographically located within upland watersheds, cannot be included within the category of 'watershed management programmes' precisely because of their sectoral/departmental conception and organisation, the lines of which run independently across the hydrological boundaries by which watersheds are defined.

Contrasting with these programmes are others that have been conceived from the outset within a watershed/land and water management framework. They include would-be holistic programmes with the terms watershed or micro-watershed development in their titles; and others, focused in a somewhat more disaggregated way, on soil and water conservation or on water harvesting. It is on these kinds of programme that the rest of this paper focuses.

UPLAND WATERSHED MANAGEMENT: IN SEARCH OF PRINCIPLES

It is a priori unlikely that many useful generalisations could be made about upland watershed management that were not to some degree contingent on local circumstances, simply because of the great variability of conditions among such watersheds, as well as within each one. While one would hope to identify a few basic principles of good management that were universally valid, others could be expected to be highly dependent on certain key variables, including:

- The nature of the physical environment (water regime, soils, topography, production potential)
- The nature of the socio-economic environment (demographic characteristics, social structure, land tenure, market linkages, etc.)
- The range of feasible new technology options, especially with respect to the capture and use of scarce water
- The availability of existing institutions, or the scope for creating new ones, with capacity to plan and manage those new technologies successfully.

A review of some recent literature has attempted to generalise about the subject and suggests that we are still a long way from having a coherent analytical framework that would enable questions of institutional choice to be systematically addressed. Some of those who have been prepared to offer technical prescriptions across a wide range of physical and social contexts are either unclear about the kind of management institutions that would effect the desired changes or give no explanation as to why the institutions they favour would be appropriate. Others have given much more thought to the interplay of physical, social and technical factors in determining appropriate forms of management, but their observations often relate to only a limited range of micro-environments and many questions about higher-level organisation tend to be left inadequately answered.

TWO VIEWS FROM THE TOP

Within the first category fall recent publications by Sir Charles Pereira (1989) and the World Bank (Doollette and Magrath, 1990). Pereira's book calls for urgent investment on a massive scale to protect whole river basins, especially their downstream portions, from the mounting flood and other damage being caused by upstream population pressures. In place of "rural rehabilitation schemes [that] are treating many individual [small] watersheds ... a solution can be reached only by the governments administering these threatened river valleys" (p. 6).

The book has the merit of dealing with all aspects of upland land use, including forestry and livestock as well as rainfed cropping and of seeking to match choice of technology to a wide range of different agroclimatic conditions; and it rightly emphasises the critical importance of water conservation and sparing but timely local irrigation in drought-prone upland conditions (e.g. pp. 98, 169). But when it comes to how the proposed new investment programmes are to be planned and managed, no clear picture emerges other than that work should be directed by some kind of government authority with the necessary technical expertise; and that the role of local people is to learn and "co-operate" (e.g. pp. 170, 209, 213). No account is taken of the extremely limited financial and manpower resources available to many Third World governments, especially in Africa; nor is there any recognition of the need to win the support of local people as active participants in the planning and management process.

If there is any dominant management model in Sir Charles's mind, it is probably the Tennessee Valley Authority (TVA)(that "classical watershed development programme", pp. 198-9). The great virtue of the TVA approach, which is of course feasible only in the context of major dams, is that it is designed to generate substantial revenue (especially from hydroelectricity) for investment in upland development - something that is otherwise in scarce supply. Unfortunately, attempts to replicate the model in developing countries - e.g. through the Damodar Valley Corporation (DVC) in eastern India and the Athi River Authority in Kenya - have not been particularly successful. An important reason in the DVC's case has been the dominance of downstream interests and a failure to take the interests of poor, backward, 'tribal' upstream inhabitants seriously. A more general problem with such 'Authorities' is that they have historically tended to take a top-down, blueprint approach to the development of upland areas that is quite inappropriate to the needs of the people who live in those 'complex, diverse and risk-prone' (CDR) environments.

The World Bank publication differs from the Pereira book in several important respects: it deals with watershed development in Asia only (in fact, most of the field evidence comes from parts of India and Java); it deliberately avoids discussion of downstream effects; the focus is on a relatively narrow range of technologies and farm management practices concerned with improving rainfed agriculture through better soil and water conservation techniques; and it recognises that, "despite the existence of soil conservation agencies and management authorities, the real managers of these lands are the local farmers and villagers" (p.1). Though a useful source of technical information and ideas, the most striking feature of a publication that purports to give advice on a continental scale is the curiously partial and limited view that it offers of development options. Manifestations of this are:

- A remarkable absence of detailed discussion about the influence of different physical factors, especially rainfall, on the choice of soil and water conservation technologies

- A bias against any kind of 'structural' intervention (e.g. contour bunding, checkdams, water harvesting structures) under any circumstances (e.g. pp. 17, 71ff., 97ff.)

- A very restricted interpretation of the meaning of 'watershed development', to the extent of making it synonymous with 'rainfed/dryland agricultural development'.

The chief explanation of this tendency towards a narrow reductionist solution, despite acknowledgement of the great variability of upland environments (e.g. pp. 2, 16), lies in the supposed universal applicability of vetiver grass - the World Bank's miracle cure for all upland environments, apparently. The Bank's excessive faith in this plant, and the distortions it has introduced to the rest of its strategic thinking, are graphically illustrated in the following passage from the Doollette and Magrath publication:

> "Currently, two complementary strategies for the development of conservation-oriented upland farming are evolving. The first is the adoption of a problem-solving approach aimed at identifying, on a site-specific basis, the key constraints to and opportunities for expanding output. The second, possible because of the uniquely non-site specific characteristics of vetiver grass, ... is the widespread use of this grass as a contour hedgerow" (p. 10).

An additional factor contributing to the limited 'rainfed agriculture' definition of watershed management (and manifested in the avoidance both of larger river-basin issues and of upland water harvesting possibilities) appears to be a 'sectoral' perspective that subscribes to the view that upland watersheds should be the responsibility of agricultural development agencies, while anything to do with water development should be left to the water/irrigation engineers. This sharp and unhelpful dichotomy is very apparent in the way most watershed development programmes have been designed in India. Thus, in the State of Karnataka the leading agency for upland watershed development is called the Dryland Development Board; and it excludes from its consideration not only large river-basin management issues but also the improvement of the numerous tanks (small reservoirs) that lie within the upper catchments and form an integral part of their hydrology. It seems that aid agencies too find it difficult to break away from old habits of sectoral and departmental thinking.

Another weakness of the publication is its perfunctory treatment of organisation and management issues. Reading between the lines, one is led to understand that there should be some kind of project authority at the "typical" watershed level (of around 100 000-200 000 ha); that the sub-watershed (5000-15 000 ha) provides the basis for a "convenient planning unit"; and that, to ensure locally-acceptable solutions, consultation should be held with farmers at the micro-watershed (500-2500 ha) level (p. 23). But there is no discussion of how to involve farmers as active participants in the planning process or how to build on their own indigenous soil and water conservation practices.

ALTERNATIVE VIEWS FROM BELOW

A very different view of possible options and strategies is offered by a number of publications that argue the need to build the development process from the bottom up, on the basis of an intimate understanding of local people's conditions and needs and of their own indigenous knowledge and practices. Among these is an exceptionally well-argued report on soil and water conservation in sub-Saharan Africa from IFAD (1992) and several others from India (e.g. SPWD, 1989; ICRISAT, 1991) that come to similar, though not identical, conclusions.

The IFAD report starts with a critique of the "dismal record" of colonial and post-colonial efforts in Africa to combat soil erosion through conservation projects that have "relied on sanctions and penalties to achieve their targets" (p. 9). It then discusses some more recent approaches that have been based on the recognition that "technical remedies can only succeed if attuned to socio-economic constraints" and that the participation of the resource users themselves is vital to success. This implies making use of traditional skills, working through existing local institutions, and involving the intended beneficiaries in the process of project identification, design and implementation. Because of the wide range of different environmental and socio-economic conditions within the region, it is only by these means that the appropriate location-specific technical solutions can be found (ibid).

In elaboration of this general argument, the report makes many important contributions towards a better understanding of some of the basic principles that seem to underlie good upland watershed management. The following are among the most noteworthy:

(a) A wide range of indigenous "ethno-engineering" practices can be found across sub-Saharan Africa, with technical designs varying greatly in response to physical conditions (rainfall, soils, topography) and socio-economic conditions (including population density); these not only provide the starting-point for improvement plans in particular localities but provide scope for the development of a more general typology of technological options likely to be suitable in different environments (pp. 24 ff and see also Reij, 1991).

(b) If they are to be sustainable and replicable, intervention programmes must be low-cost: this means going for vegetative methods of conservation wherever possible, but does not rule out "engineering structures" in some contexts (p. 40).

(c) Interventions must also lead to short-term, sustainable yield increases: "Conserving soil for future generations is not an argument that will convince resource-poor land users to engage in soil and water conservation. Short-term yield increases of 15-20% in the first year may not be sufficiently attractive to farmers. Net increases of 50% will be more convincing. In arid and semi-arid regions, water harvesting and moisture conservation techniques often permit such increases" (p. 72 and see Tiffen 1992 for evidence from Machakos district, Kenya).

(d) If farmers are to be offered any subsidy, the levels should be carefully calculated on the basis of macro- and micro-economic considerations (pp. 73-74).

(e) Such programmes require long-term commitment on the part of the external support agency (p. 9).

(f) The development process should "start from below and work upwards" (p. 74). The most effective entry-point is at the individual farm level and the village boundary provides a better basis for local planning decisions than a strictly-defined hydrological watershed. Although "from a hydrological point of view, the catchment presents the rational and technically appropriate unit of intervention for soil and water conservation", farmers and village communities rarely perceive it as such; and the fact that it has been used in the past as the basis for enforcing 'top-down' measures leads the authors to conclude that "any return to catchment planning or conventional watershed management should be viewed with caution" (pp. 61, 71).

(g) Soil and water conservation work is best integrated into the larger framework of agricultural extension programmes; new organisations and separate cadres should not be created for the purpose (p. 70).

One point that does not emerge clearly from the IFAD report is the basis on which larger programmes should be organised. Points (f) and (g) suggest that there is no need for a larger watershed-based organisation - that it may indeed be positively undesirable; and the implication seems to be that a fairly scattered and 'atomised' village-by-village approach would be acceptable. Given that experience in the use of participatory methods is still quite limited, it is probably fair to conclude that most of the work described is still in a pilot phase and that further thought is still required about larger questions of programming and project organisation (Reij, 1991).

Recent experience with participatory approaches in South Asia come to strikingly similar conclusions, except with the respect to the unit of local organisation (village versus micro-watershed) and the basis for organising at the project and programme level. Thus, in place of a long history of past failure on the part of government schemes that have attempted to impose certain standard soil conservation practices on unwilling farmers, it is argued that the only hope of achieving sustainable success can come from first understanding existing indigenous practices and then superimposing improvements on them in close consultation with the farmers concerned (ICRISAT, 1991). While there is agreement with the IFAD report that the easiest basis on which to gain acceptance of improved technologies is through interventions at the individual farm level "that require minimal group action" (ibid p. 17), there is also evidence from different parts of the region that, in certain circumstances, farmers can and do work closely together to achieve common benefits. Thus, in the hills of Nepal, "farmers are capable of creating and maintaining large and complex multi-member systems to achieve mutually beneficial results", including shaping field ridges in long and complex patterns, shaping terraces to suit topographical differences, and using inverted siphons to transport irrigation water (p. 21). Moreover, an increasing number of NGOs are finding ways of successfully combining a village-based approach to local organisation with a micro-watershed-based work programme, through the use of Participatory Rural Appraisal (PRA) techniques (p. 35, 38 and see SPWD, 1989; Shah *et al.*, 1991). In at least one case - a project in northern Karnataka, involving a partnership between a donor agency, the state government watershed development agency and an NGO - a project structure has been created whereby a 55 000 ha watershed is being developed through a management hierarchy that is ultimately based on 37 village/micro-watershed societies (pp. 35 ff.); and other NGO networks with similar potential higher-level linkages with government agencies are developing elsewhere in India (SPWD, 1989).

The differences between the African and South Asian perceptions about the scope and desirability of organising development on a hydrological watershed basis may stem from a number of factors. The principal reasons may be significant differences in local topography (typically large, flat river basins in Africa versus steeper upland watersheds in much of South Asia) and population density (relatively low in Africa versus much higher densities in South Asia, leading to a closer congruence between village and micro-watershed boundaries). Another factor may be the greater involvement of NGOs in this type of work in many parts of South Asia and their capacity, through PRA, (a) to help villagers address common property management issues that still appear problematic in African conditions (IFAD, 1992); and (b) to empower them to deal effectively with government agencies that would otherwise be inclined to impose standardised top-down solutions.

In South Asia, as in sub-Saharan Africa, the extent to which farmers are likely to find it necessary or attractive to undertake collective action, particularly with respect to water conservation and management, will vary greatly according to rainfall conditions (see, e.g. Ray, 1986 in conjunction with Reij, 1991). Thus, in areas of very low rainfall heavy investment in water harvesting structures is common; in the 400-700 mm annual rainfall range the main reliance is on *in situ* moisture conservation in individual fields, unless there is also scope for groundwater exploitation; and in higher-rainfall, higher-runoff conditions (rising up to 1500 mm/year in eastern India) major returns become possible from small-scale water storages, especially if the stored water is applied to high-value horticultural crops or agroforestry systems.

In all these conditions, and especially the last, there can be little doubt that, in principle at least, a soil-and-water conservation/micro-watershed approach offers far better opportunities for substantial increases in rural incomes than more narrowly defined sectoral programmes such those based on 'pure' rainfed FSR/E. Experience with the latter in high rainfall areas in eastern India suggests that they would be greatly strengthened if they were placed within a watershed management framework that allowed them to incorporate action in support of community-based water conservation and management (Bottrall and John, in press). The same argument could be extended to social or community forestry programmes.

SOME CONCLUDING PROPOSITIONS

Clearly there is still much to be learnt about the principles on which appropriate choices should be made both with respect to the technologies and the institutions of upland watershed development. However, on the basis of the evidence presented in this paper, it seems permissible to conclude with the following broad propositions, some of which, however tentative, may serve as useful initial guidelines for future programme development:

1. Substantial public investment in upland watershed development appears strongly justified on both equity and sustainability grounds, particularly in view of many countries' long history of neglect of, and discrimination against, the interests of large numbers of poor upland people; and in some higher rainfall contexts, the economic returns to such investment could also be very high, exceeding returns to investment in conventional downstream irrigated agriculture.

2. For the same reasons, in any larger exercise aimed at achieving reforms in water resources policy through the use of market mechanisms to reallocate water among different uses, it would be justifiable to protect the interests of current and prospective upland water users by means of substantial cross-sectoral public subsidies (though there is no reason why government should bear 100% of the investment costs, given the evidence that farmers may often be willing to contribute a significant proportion themselves - see e.g. ICRISAT, 1991; IFAD, 1992.

3. Given that water is likely to be 'the key physical resource limiting or triggering economic development' within a watershed, farmers will be most responsive to other measures, including soil conservation, if they are also combined with quickly realizable benefits from water conservation; and strategies that do not necessarily include water conservation measures (such as those employing FSR/E approaches) will be enhanced by their inclusion - provided the extra benefits are not outweighed by the extra financial and management costs.

4. Given the wide range of possible rainfall and other physical determinants of local context, appropriateness of technology must be highly contingent on those factors; and any proposed strategy that offers relatively undifferentiated technical solutions irrespective of those factors must be open to serious question.

5. Conservation measures that can be carried out at the individual farm level are intrinsically easier to accomplish than those requiring community action. In most lower rainfall (<700 mm) conditions, the need and scope for larger, community-level investments is limited, but they and the potential benefits increase markedly in higher rainfall, higher run-off conditions.

6. The complex, diverse and risk-prone (CDR) nature of upland watersheds gives a high premium to local indigenous knowledge and to participatory methods of planning and management, especially at the micro-watershed/village level. Here, external agencies will be most effective if playing a responsive, enabling role. Conversely, they will be least effective if they use a top-down, undifferentiated package approach - especially if they are the same agencies that were previously involved in attempts to enforce conservation. Any strategy based on the assumption that government agencies can directly manage watersheds is doomed to fail.

7. Government agencies have historically been organized to address issues on a fragmented sectoral basis, with a consequent tendency to miss important ecosystem linkages and an inability to support an integrated approach to watershed development. However, if they are required to promote such an approach, the conventional bureaucratic response will tend to have high administrative costs (inter-departmental coordinating committees or a new multi-sectoral agency). By contrast, farmers find it relatively easy to think holistically about the multi-faceted development of the particular micro-watershed they live in and they are often capable of planning and managing a sequence of 'multi-sectoral' activities (such as soil and water conservation, followed by modifications in tree, crop and livestock management) without recourse to complex institutional arrangements. It may therefore be possible to keep the administrative costs of integrated watershed development within acceptable limits by delegating a large part of local management responsibilities to farmers' organisations and, wherever possible, NGO intermediaries.

8. Such a division of responsibilities would allow more government agency resources to be allocated to the predominantly planning functions at meso- and macro-watershed levels without which no watershed management programme would be complete. Key functions here would be the collation and analysis of available hydrological data and use of the results to establish water allocation principles and water rights at different levels within the watershed. This could eventually provide the basis for a larger watershed organisation capable of participating in the kind of upstream/downstream planning and adjudication process envisaged by Hamilton and King at the drainage basin level.

9. A possible strategy for a donor agency to consider might thus contain the following elements:

- support for NGOs to mobilise people at village/micro-watershed levels for local-level planning, using PRA methods
- support for R&D of new technologies - for low-cost water conservation, conveyance and application; and sustainable and sometimes potentially high-return farming systems
- help in developing a viable, low-cost (government or non-government) technical support system at a higher 'watershed' level, to support the needs of micro-watershed villages, as the programme builds up
- where appropriate, creation of linkages with a larger watershed inventory and planning exercise (and/or a larger rural/district development programme)

- provision of training in new methods and techniques, including PRA, R&D/Extension (in place of conventional FSR/E), and watershed inventory and planning.
- support for monitoring, not only of impact but also of processes, with a view to wider programme replication.

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DISCUSSION

It was suggested that there might be a danger of institutionalising a pattern of water management which could be inflexible and rigid. A 'bottom-up' approach was advocated in which links to higher levels should be constructed; new approaches should be embedded in community knowledge and involve NGOs. It was said that the case had been presented in the paper for upland watershed management but the same conditions do not apply in the lower catchments. In addition, there are great differences between the intensive and extensive farming systems.

PAPER 10

The hydrological impact of land-use change

(with special reference to afforestation and deforestation)

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Summary: We live in a changing world and the effects of the changes are of interest to us all. On a global scale the most significant land-use change in terms of land area, and arguably also in terms of hydrological effects, involves afforestation and deforestation practices. In the tropics, the deforestation of indigenous forests continues as land is converted to agriculture to feed increasing populations though the balance of forested land is being partially redressed through commercial afforestation of fast growing, often exotic, tree species. In contrast, in the developed world, and particularly within Europe, the balance of forested land is likely to increase as a result of improved agricultural productivity and food surpluses and a move to 'set aside' policies for agricultural land. Planting trees creates concern that they will intercept more rainfall during wet periods and, because of their deeper root systems, transpire more water during dry periods and thus deplete groundwater and downstream surface water resources; acidification may also result. Cutting down trees raises concerns of erosion, siltation of streams and increased leaching of soil nutrients. Forests are also likely to have beneficial effects on climate, at all scales ranging through micro to meso and global. These and other issues are discussed in relation to recent experimental studies into the hydrological impact of temperate forests in the UK, indigenous tropical forests in Indonesia and Brazil and of *Eucalyptus* plantations in southern India. A summary of the expected impacts of forests in relation to water yield, floods, low flows, water quality, erosion and climate is presented.

INTRODUCTION

Forests are generally regarded as being beneficial to the environment. Bio-diversity and global climate issues in relation to forests received high priority at the UNCED conference. However forest impacts on the environment may not always be beneficial; although forests, through increased evaporation, generally have a favourable effect on climate, forests, because they evaporate more water than other vegetation types, are likely to deplete surface and groundwater resources. Both water and forests are central to the development of many LDC's economies; wood is required for buildings and for fuel for local people and timber is required for paper and rayon-based industries. Plantation forests, with high water-use efficiency, can meet these needs and take the pressure off remaining indigenous forests, whilst minimizing the effects on water resources.

The impacts of forests on the environment are not always easy to assess because many competing processes are often at work and the net result cannot always be predicted accurately with current knowledge. Research may still be required. Nevertheless many of these impacts are now fairly well understood and this paper attempts to summarise these impacts so that the environmental implications of forests are better understood in relation to development projects.

The hydrological impact of forests has always been a contentious issue. Within the UK the effects of coniferous afforestation of the uplands on water quantity and water quality stimulated many studies both at the process study and catchment scale. More recently the effects of broadleaf afforestation of the lowlands of the UK and the European Community as a result of 'set aside' policies have received more prominence. The issues raised in relation to the hydrological impact of forestry in the tropics and in developing countries are perhaps the most serious. It is often in these countries that water represents one of the most important constraints on development and where any adverse effects on water resources should be viewed with concern. The effects of eucalypt plantations on water quantity have aroused controversy in many tropical and subtropical countries including India, Kenya, Uganda, South Africa and Portugal and have stimulated a large ODA-funded research projects in Karnataka, southern India. The water relations and climatic impacts of tropical rainforests have also received great interest and ODA have funded projects in Indonesia and more recently in Brazil with the Anglo-Brazilian Amazonian Climate Observation Study (ABRACOS). Concerns over the hydrological impacts of tropical plantation forestry are not restricted to eucalypts, tropical pines are also under scrutiny. One of the principal objectives of the ODA forestry programme, involving pine plantations, in Sri Lanka was to 'regulate' the flows to the Victoria water supply and hydropower reservoirs and, thereby, to reduce erosion. However, current hydrological knowledge would suggest that the impacts of the plantations, in the areas where they are currently being planted, are likely to reduce flows overall and may even increase erosion. Nevertheless, planting at higher altitudes in Sri Lanka, where cloud deposition to forests may be a significant process, holds the promise of improving water resources.

In this paper current knowledge on some of the hydrological impacts of forests is outlined, particularly in relation to ODA-funded research projects in Indonesia, Brazil and India. Further details of the hydrological impacts of land-use change including the impacts of forestation, agricultural intensification, and the drainage of wetlands are available in recent publications (Calder, 1990; Calder, in press).

HYDROLOGICAL IMPACTS AND PROCESSES

Water quantity

The higher water use of forests compared with shorter vegetation is due principally to two processes. In wet areas of the world, such as the uplands of the UK, the high aerodynamic roughness of forests leads to greatly enhanced evaporation rates in wet conditions (interception) and evaporation can, on an annual basis, be as much as twice that for grass. In drier climates the deep root systems of forest and their greater water availability during dry seasons leads to higher transpiration losses. The water-use studies carried out under the ODA-funded eucalypts project in the dry zone of southern India have established that the total evaporation (transpiration plus interception) from forest is nearly 1.5 times greater than from agricultural crops.

Annual flow: Annual flow results from catchment experiments have been reviewed by Hewlett and Hibbert (1967) and Bosch and Hewlett (1982). From an analysis of results from 94 catchments world-wide Bosch and Hewlett concluded that:

- Pine and eucalypt types cause an average change of 40 mm in annual flow for a 10% change in cover with respect to grasslands, that is, a 10% increase in forest cover will decrease annual flow by 40 mm, a 10% decrease in cover will increase annual flow by the same amount.
- The equivalent response on annual flow of a 10% change in cover of deciduous hardwood or scrub is 25-10 mm, that is, if 10% of a grassland catchment is converted to hardwood trees or scrub vegetation, the annual runoff will decrease by 10-25 mm.

Although the impacts on annual flow are related to local climate and soil characteristics, an overall reduction in flow is to be expected, with few exceptions, from forests world-wide. Better quantification of the impacts in a particular area can be achieved if the limits on forest evaporation can be identified. The uplands of the UK, subject to a maritime climate typified by high rainfall, a high number of raindays per year and high windspeeds, are an example of a situation where large-scale advection is the principal limit on forest evaporation. In the UK uplands, the total evaporative losses from forest can consume an amount of latent heat that easily exceeds the radiant energy input to the forest (Table 1).

TABLE 1
Observations of the annual water and energy balance of moist tropical and temperate forests

Region	Rainfall (mm)	Transpiration (mm)	Interception (mm)	Evaporation (mm)	Radiation (mm equivalent)
Indonesia West Java August 80 - July 81 (Calder *et al.*, 1987)	2835	886	595 (21%)	1481±12%	1543±10%
Brazil Amazonia, 1984 Reserve Ducke Forest (Shuttleworth, 1988)	2593	1030	363 (13%)	1393	1514
Wales Plynlimon, 1975 (Calder, 1978)	2013	335	529 (26%)	864	617

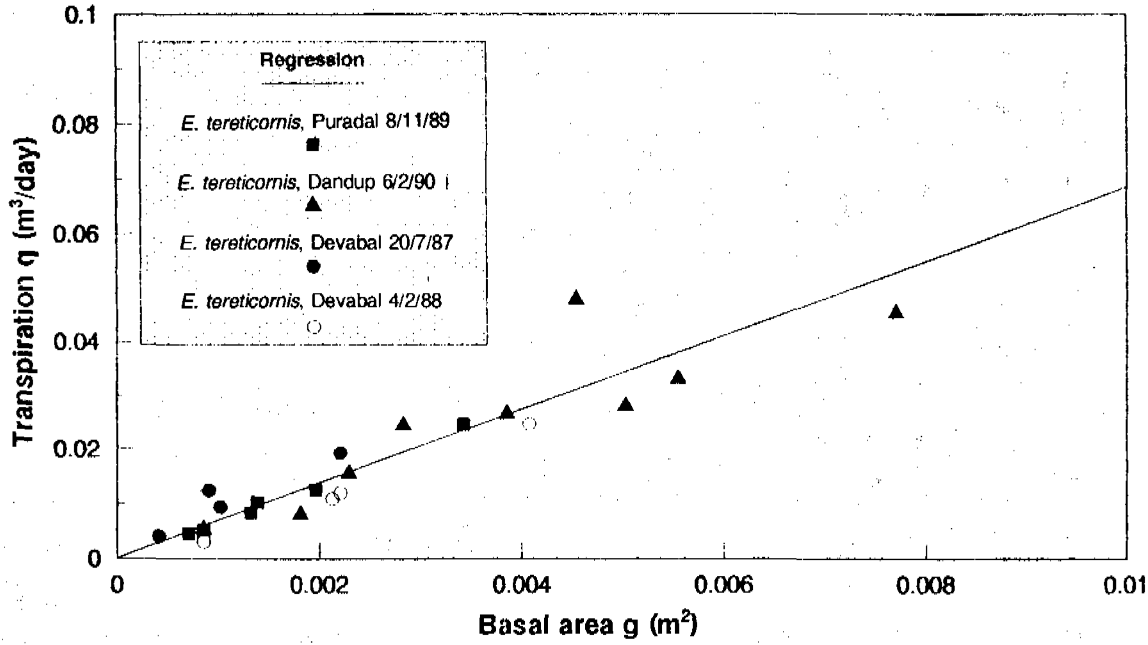
Note: The Amazonia site experiences dry periods which may limit transpiration

The wet evergreen forests of the tropics represent another situation where climatic demand is likely to limit forest evaporation. However, climate circulation patterns in the tropics do not favour large-scale advection of energy to support evaporation rates and here evaporation rates are likely to be closely constrained by the availability of solar radiation (Table 1). As humid rain forest is able to convert, on an annual basis, virtually the equivalent of all the net radiation into evaporation it is unlikely that any other land use will be able to evaporate at a higher rate and conversion of forest to annual crops in these areas will increase annual flows.

In very low rainfall areas the principal limit on annual evaporation is soil water availability. Studies in Karnataka, southern India (Harding *et al.*, 1992), show that the available soil water capacity of both indigenous, dry deciduous forest and *Eucalyptus* plantation is of the order of 480 mm whereas, in the same region, the available water capacity for finger millet, an annual agricultural crop, is 150 mm. The annual evaporation from the indigenous and plantation forests is, within the errors of measurement (10%), equal to the rainfall of 800 mm/year the evaporation from the finger millet, with a reduced soil water reservoir to exploit, is 500 mm/year. Conversion from forest to agricultural crops in this area will therefore increase annual flow (or catchment recharge) by this difference in annual evaporation. The studies also demonstrated the importance of tree size and age as limiting factors on evaporation. Measurements made on these (young) *Eucalyptus* plantations have established a new and surprisingly close correlation, Figure 1, (Calder *et al.*, 1992) between the transpiration rate of an individual tree and its stem cross-sectional area (a better correlation than was found with leaf area). This relationship, when expressed in terms of the total stem cross-sectional area of the stand per hectare, and with the use of a suitable soil moisture regulating function, enables the stand evaporation to be calculated and has been used in models to predict the evaporation, the soil moisture deficit and the volume growth (Calder, 1992) and will be used in the future to improve the water-use efficiency of the stands. The only meteorological data that are required are daily rainfall. Meteorological demand, although providing the driving force for evaporation, is not thought to be a limiting factor during most of the year; the principal limitations on transpiration are thought to be soil moisture availability and tree size. These results from semi-arid Karnataka, which indicate that evaporation is limited principally by soil water availability and plant physiological controls, are therefore in direct contrast to the observations from the wet uplands of the UK where evaporation is principally limited by atmospheric demand and physical, aerodynamic controls.

FIGURE 1

Transpiration rate of *Eucalyptus tereticornis* trees in conditions with little soil moisture stress at sites in Southern India - measured using the deuterium tracing method plotted against the basal (stem) cross-sectional area of the tree measured at 1.2 m above ground level



$q = (6.63 \pm 0.33)g$ (m^3/day)

$q = (0.663 \pm 0.033)G$ (mm/day) G units: m^2/ha

$r^2 = 0.85$

NB The gradient of the regression line, 6.63 ± 0.33 m/day has units of velocity and represents the Darcy velocity of sap flow in the stems

Source: Calder *et al.*, 1992

Seasonal flow: Afforestation may affect seasonal flow through two principal mechanisms. Firstly, the higher interception losses from forests in wet periods and increased transpiration losses in dry periods (because of deeper root systems) both tend to increase soil moisture deficits in dry periods compared with those under shorter crops. These increased deficits lead to reduced dry-season flows where part, at least, of the dry-season flow is derived from the soil reservoir. Secondly, land drainage operations, which are often part of the management associated with afforestation in wet, temperate climates, tend to increase flows as a result both of the initial dewatering (which may take a number of years) and through the long-term effects of the alteration of the drainage regime. The two mechanisms are opposing and the net effect on low flows may result in either higher or reduced low flows but in the long term, when trees have reached maturity, it is expected that the effects of increased evaporation will predominate and low flows will be reduced.

Cloud forest: For high-altitude forest, or cloud forest, which is above the cloud base for a significant proportion of the year, the deposition of cloud water onto the forest is likely to be a significant hydrological process. Because of the reduced aerodynamic transport of water vapour above forest, and increased leaf area of forest, compared with shorter crops, the cloud deposition rates onto forest will be many times greater than those onto short vegetation. For cloud forest in locations such as the Andes, Hawaii and Sri Lanka cloud-water deposition may provide a significant component of the dry-season flow in rivers.

A further example of a situation in which forests may assist in supporting dry-season flows is where forests are being used to reclaim degraded lands. There is some evidence to suggest that, where forests have been planted in India in degraded areas with laterite outcrops, the increased infiltration of rainfall into the soil beneath the forest exceeds the extra evaporation from the forest and recharge to groundwater aquifers is increased.

Water quality

There is greater awareness that there are not only water quantity but also water quality implications of afforestation; forestry has been associated with catchment acidification. Interestingly, process studies have identified that the same process is responsible for both increased evaporation in wet conditions and increased acidification. The higher aerodynamic transfer of water vapour and heat between the surface of the forest vegetation and the atmosphere, in comparison with shorter vegetation, allows the high evaporation rates of intercepted water (interception) and higher deposition rates of pollutants in the dry form as reactive gases and particles and in the wet form as pollutants contained within cloud and mist droplets. Cloud and fog water contain significantly larger ionic concentrations than rain with peak concentrations up to 50 times greater (UK Review Group on Acid Rain, 1990). Recent studies (Fowler *et al.*, 1989) indicate that for high-altitude forests in the UK (~ 500 m), altitudes sufficient for forests to intercept cloud and mist droplets frequently, the deposition of sulphur particles contained within cloud droplets (5-10 μm radius) may make a large contribution to the total annual deposition. Because cloud droplets, as opposed to sub-micron-sized dry particles, are efficiently captured by vegetation surfaces, and as forests have lower aerodynamic resistances compared with shorter vegetation, deposition rates of cloud-borne pollutants onto forests will be greater than deposition onto shorter crops.

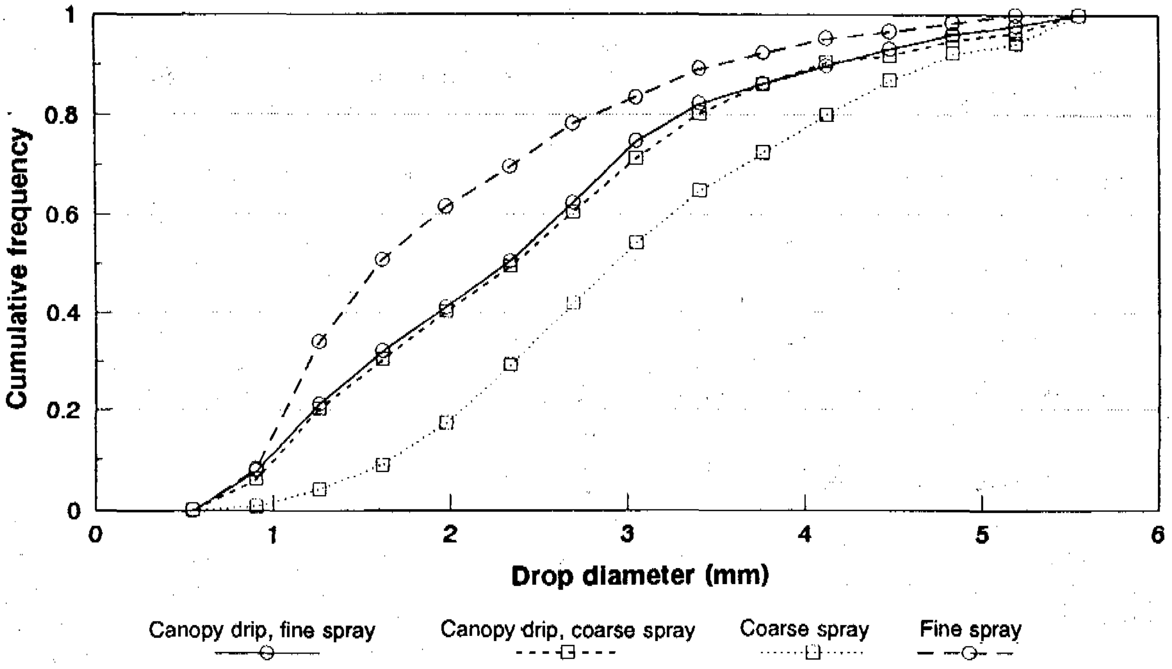
The most disruptive effects of forestry on water quality arise through intensive management practices associated with harvesting, site preparation and site management. In particular, clearcutting can result in large increases in nutrient concentrations in watercourses. The highest concentrations reported in the USA are from forests in New Hampshire. Hornbeck *et al.* (1975) and Pierce *et al.* (1972) report values of 26 mg/dm^3. More commonly values of about 1 mg/dm^3 have been reported for other forests in America. The increased nutrient concentrations affect lake and stream eutrophication and increase the outbreaks of phytoplankton blooms.

Forestation and erosion

Forestry operations are often associated with increased erosion. Land drainage operations prior to afforestation, the construction of access roads, felling operations involving soil compaction and disturbance all increase erosion as they do flooding. The presence of the forest also affects erosion. Principally these are through the effects on slope stability and on splash detachment. In relation to slope stability O'Loughlin and Ziemer (1982) state that the positive influences of forests on erosion depend upon the reduced soil pore water pressure caused by the forest evaporation, accumulation of an organic forest floor layer and mechanical reinforcement of the soil by tree roots. Negative influences result from windthrow of trees and the weight of the tree crop itself.

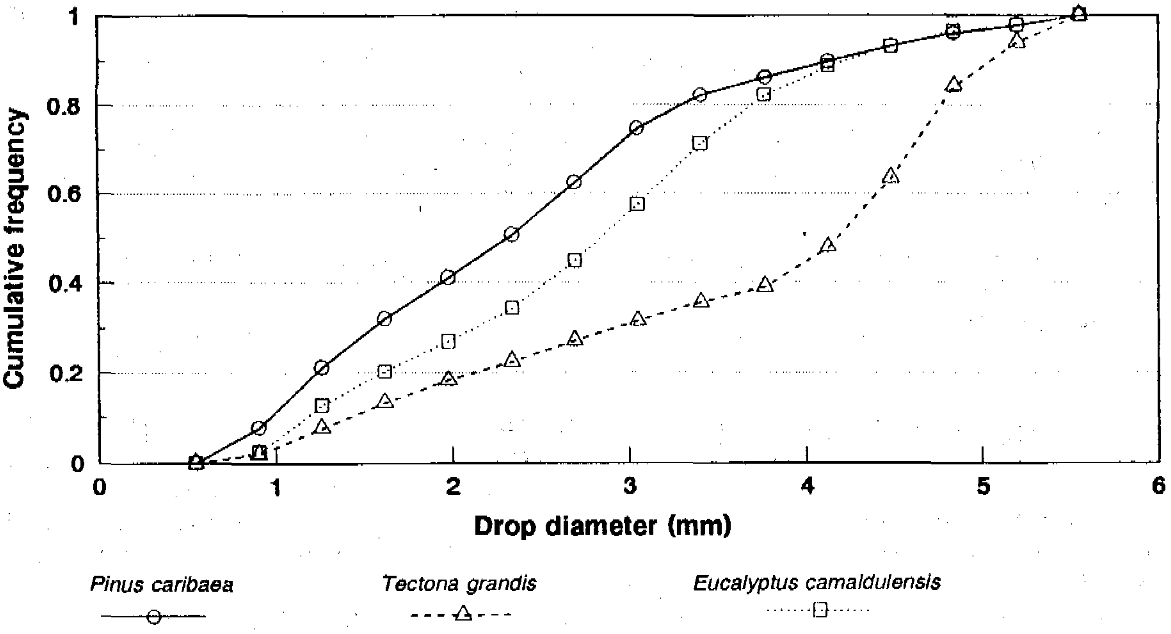
Vegetation canopies influence splash detachment through the modification of the natural raindrop size spectrum. Contrary to popular belief forest canopies do not necessarily 'protect' the soil from raindrop impacts. For storms with small raindrop sizes, usually low intensity storms, canopies tend to amalgamate drops until vegetation elements are fully wetted and larger drops are released as net rainfall. Depending upon the height of the vegetation above the ground (drops of up to 6 mm diameter will reach terminal velocity within 12 m) drops may approach terminal velocity and acquire a *higher* kinetic energy than those in the natural rainfall (Morgan, 1985). The potential for greater splash detachment from bare mineral soils is therefore *greater* under tall forest canopies than under shorter vegetation. Conversely, for storms with the largest drop sizes, usually the higher intensity storms, vegetation canopies may break up the large drops and reduce both the mean drop size and the mean kinetic energy of the incident rain. The *Eucalyptus* water-use studies in India (Hall and Calder, in press) have shown that vegetation canopies have characteristic net rainfall spectra. For *Pinus caribaea*, irrespective of the drop size spectra of the incident rain the throughfall spectra remain essentially unchanged (Figure 2) and retains a 'signature' characteristic of this particular vegetation type. For three tree species studied, *Pinus caribaea, Eucalyptus camaldulensis* and *Tectona grandis*, median volume drop diameters of the throughfall ranged from 2.6 to 4.6 mm (Figure 3) whilst corresponding drop kinetic energies, assuming the drops reached terminal velocity, ranged by a factor of 7 with *Pinus caribaea* having the least and *Tectona grandis* the greatest kinetic energies.

FIGURE 2
Cumulative frequency distribution of throughfall drop spectra beneath *Pinus caribaea* subject to spray with median volume drop diameter (the drop diameter for which 50% of the volume was in drops less than this value) of 3.2 mm and 1.9 mm



NB Median volume drop diameters of the throughfall spectra for *Pinus caribaea* was 2.6 mm, for *Eucalyptus camaldulensis* was 3.1 mm and for *Tectona grandis* it was 4.6 mm

FIGURE 3
Cumulative frequency distribution of throughfall drop spectra for three tree species subject to spray with median volume drop diameter (the drop diameter for which 50% of the volume was in drops less than this value) of 3.2 mm.



Splash detachment mobilises soil particles which can be transported if there is surface runoff. These small soil particles can clog surface micropores and macropores leading to an impermeable crust which itself reduces infiltration and enhances the production of surface runoff. In natural mixed forests, where a surface vegetation cover or a deep litter layer is usually present which helps to protect the soil surface from raindrop impact, and where infiltration capacities are high, surface runoff and surface erosion are usually minimal. For plantation forest the understorey cover of vegetation is often reduced by shading or through competition for soil water or nutrients. For some plantations outbreaks of fire are a common occurrence which destroy both understorey vegetation and litter layers. Plantations which have both tree species with large net raindrop spectra, such as *Tectona grandis*, and a lack of understorey or a litter layer have the potential for particularly high rates of soil erosion.

Climate

Land use affects climate. Depending upon the scale of the land-use change the effect can occur on a micro, meso or global scale. The effect occurs principally through the different inputs, into the atmosphere, of heat, water vapour and radiation from the different land surfaces. The variation with height of temperature, humidity and windspeed close to a surface is the result of a balance between externally applied climatic variables, the surface fluxes of heat and water vapour, and the aerodynamic properties of the surface. Differences in the water availability at the evaporating surface will produce marked differences in micro-climate as a result of altering surface fluxes of heat and water vapour. An extreme example is the cool, moist micro-climate found over a forest which has a deep root system and readily available soil water as compared with the hotter, drier micro-climate found above a short-rooted crop or a bare soil (where evaporative fluxes will be much less). For land-use changes occurring over areas extending for tens of kilometres the height of the planetary boundary layer (the height of the cloud base) may be altered and meso-climate change may occur. The scale of the effect is poorly understood at present and warrants further research. Similarly, the alteration of surface fluxes of heat and water vapour as a result of land-use change may have an impact on global climate. The Brazilian ABRACOS project, funded by ODA, is seeking to parameterise the surface fluxes from Amazonian rain forest for use in Global Climate Model (GCM) predictions of climate change.

Rainfall

The question of whether the effects of a land-use change can alter rainfall is still controversial. Kitteridge (1948) concluded that the influence of forests on rainfall generation is small, less than a 3% increase in temperate climates in rainfall over forests as compared with grassland, which is caused by the increased orographic effect resulting from the height of the trees raising the effective height of the topography. Some 40 years later it is possible to say little more on the effects of land use on rainfall generation on the meso-scale, although recent developments in mesoscale climate modelling indicate that the increased evaporation of intercepted water from forests can humidify the planetary boundary layer and can lead to a 5-10% increase in the regional rainfall. Further experimental and modelling studies are required to provide information on this important and contentious topic.

A summary of the hydrological impacts associated with land-use change is given in Table 2.

CONCLUSIONS

The impact of forests and of forestry management practices is likely to have profound effects on hydrology and climate at both the local and regional scale. There may still be a requirement for research to quantify these impacts for a given environment; one such environment is the dry tropics where the major part of the worlds tropical forests reside and which support large populations but which are, at present, very poorly researched. Perhaps more importantly, research should be directed not just to quantifying the impacts, as has largely been the case in

TABLE 2
Summary of the major hydrological effects of land-use change

Land-use change	Component affected	Principal hydrological processes involved	Geographical scale and likely magnitude of effect
AFFORESTATION (Deforestation has converse effect except where disturbance caused by forest clearance may be of over-riding importance)	**Annual flow**	Increased interception in wet periods	Basin scale; magnitude proportional to forest cover, world coverage is 34 mm/year reduction for 10% increased in forest cover
	Seasonal flow	Increased interception and increased dry period transpiration will increase soil moisture deficits and reduce dry-season flow	Basin scale; can be of sufficient magnitude to stop dry-season flows
		Drainage activities associated with planting may increase dry-season flows through initial rewatering and also through long-term effects of the drainage systems	Basin scale; drainage activities cloud-water deposition may have a significant effect on dry-season flows
		Cloud-water deposition will augment dry-season flows	High altitude basins only; increased cloud-water deposition may have a significant effect on dry-season flows
	Floods	Interception reduces floods by removing a proportion of the storm rainfall and by allowing build-up of soil moisture storage	Basin scale; effect is greatest for small storm events
		Management activities: cultivation, drainage, road construction, all increase floods	Basin scale; increased floods for all sizes of storm events
	Water quality	Leaching of nutrients is less from forests through reduced surface runoff and reduced fertiliser applications	Basin scale; variable but leaching can be an order of magnitude less than from agricultural land
		Deposition of most atmospheric pollutants is higher to forests because of reduced aerodynamic resistance	Basin scale; leads to acidification of catchments and runoffs
	Erosion	High infiltration rates in natural, mixed, forests reduce surface runoff and erosion	Basin scale; reduces erosion
		Slope stability is enhanced by reduced soil pore water pressure and binding of forest roots	Basin scale; reduces erosion

Table 2 contd.

		Windthrow of trees and weight of tree crop reduces slope stability	Basin scale; increases erosion
		Soil erosion, through splash detachment, is increased from forests without an understorey of shrubs or grass	Basin scale; increases erosion
		Management activities: cultivation, drainage, road construction, felling, all increase erosion.	Basin scale; management activities are often more important than the direct effect of the forest
	Climate	Increased evaporation and reduced sensible heat fluxes from forests affect climate	Micro, meso and global scale; forests generally cool and humidify the atmosphere; a 2°C increase in regional temperature is predicted for Amazonia if deforestation continues

Source: Calder, In press

crops, irrigation, selection of species and clones for high water-use efficiency, may all have a part to play in improving the water use efficiency of plantations. With respect to indigenous forests an understanding of the processes which are responsible for their sustainability and regeneration may be crucial to their future survival. In many parts of India and Sri Lanka high altitude shola and cloud forests are receding. Similarly evergreen forests in the Western Ghats of India, which perhaps represent the only example in the world of evergreen forests which exist-in an area with a six-month dry season, show a reversion to a species composition more representative of a semi-evergreen forest when subject to disturbance. The understanding of the hydrological controls on forest sustainability is essential if these rare forest types are to be preserved for the future.

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DISCUSSION

Where transpiration rates under forest are 1.5 times the rainfall it could be assumed that the trees were mining the previous years' rainfall. In response to a question on whether the natural acidity of the soil influences the uptake of pollutants it was said that the Institute of Hydrology was looking at the transference of pollutants including the effect of the canopy roughness. It was pointed out that land-use management decisions involve numerous factors and it is not simply a question of forestry versus hydrology. Also we should not discount local perceptions such as the conventional wisdom that trees do enhance or regulate stream flow. In response it was said that anecdotal material is unreliable; 100 catchments world-wide show reduction in flow when forest is removed. Important and understated benefits of large forest blocks are the prolongation of wet season by a few days and temperature moderation with the potential to induce considerable land-use changes. Since there is a linear correlation between evaporation rates and trunk cross section it was suggested that tree size could be an excellent measure of water use, simplifying our understanding of hydrological processes on a grand scale. It was reported that in Australia water use is being estimated from the indigenous sparse *Eucalyptus* forest by remote sensing based on the assumption that leaf areas grow to use the available water.

PAPER 11

Small-scale irrigation in sub-Saharan Africa: a balanced view

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Summary: Small-scale or farmer-managed irrigation (SSI), is a promising vehicle for rural development. It can offer the farmer increased security of crop production, while avoiding many of the problems which have been experienced by large scale, formal irrigation projects. The experience of SSI can also provide pointers to the improved management of existing large scale projects. The conditions for successful small farmer irrigation development are set out, together with the implications for present practice. Key areas for research and development are identified, and the importance of national irrigation policy development and strategy formulation is highlighted.

INTRODUCTION

Since at least the late 1970s large-scale, formally managed smallholder irrigation has been the subject of increasing criticism by researchers and observers in the field and, to a lesser extent, by donors. The reasons for this barrage of criticism are numerous and have been well documented elsewhere.

In relation to Nigeria's massive investments in such irrigation projects the World Bank commented: "There can be no doubt that this sum [nearly 1 billion Naira], if spent judiciously on the promotion of rainfed agriculture and small irrigation schemes, would have produced vastly superior returns" (World Bank, 1979). Nigeria's generally disappointing experience with large-scale irrigation has been widely commented on in the academic literature (e.g. Adams, 1991; Carter *et al.*, 1983; Kimmage, 1991; Palmer-Jones, 1987; Wallace, 1981). An evaluation (van Steekelenburg and Zijlstra, 1985) of a number of smallholder irrigation projects in Africa funded by the EEC found fault with many aspects of large-scale irrigation schemes, and concluded: "In irrigation projects in sub-Saharan Africa, it would appear that the larger the projects are, and the higher the level of their technology, the poorer is their performance." In Tanzania, in the course of the UNDP-funded FAO-executed project 'Institutional Support to Irrigation Development' (1986-90), criticism of capital-intensive sophisticated schemes requiring high levels of support services grew; irrigation development policy in that country now stresses low-cost improvements requiring only limited Government inputs (Chapman, 1987).

In a number of countries it has only recently been acknowledged that the development of major water resource projects (including irrigation schemes) has damaged or destroyed existing traditional irrigation systems whose economic value was grossly underestimated.

PROBLEMS WITH LARGE-SCALE IRRIGATION PROJECTS

Through the 1980s a reaction against the promotion of large-scale irrigation projects has been gathering pace (especially, but not exclusively in Africa). With some exceptions, national governments, donors and lending agencies are starting to recognise the management issues associated with scale and philosophy of irrigation development. Just as with environmental issues, so with the subject of small-scale irrigation, it has suddenly become respectable not only to criticise large-scale projects but also to promote small-scale alternatives. Figure 1 lists more than 20 of the factors identified by evaluators of large scale irrigation projects around the world

It is perhaps not surprising then that both the British irrigation fraternity and the wider international interest group established networks in the late 1980s to promote small-scale

FIGURE 1
Reasons identified for poor peformance of large-scale irrigation schemes

PROBLEMS AT CONCEPTION AND PLANNING STAGE

- The inadequacy of conventional criteria for project acceptance
- Lower welds than anticipated in project plans
- Generally over-optimistic projections of benefits at conception/feasibility stages
- Inadequate time allowed for project preparation
- Unrealistic mechanisation strategies
- Insufficient account taken of land tenure and water rights
- Irrigation activities not integrated with rainfed cropping and other farming and income-generating activities
- Insufficient, or no, account taken of farmers' objectives

INHERENT DIFFICULTIES

- The complexity and problematic nature of irrigation as a form of agricultural intensification
- Problems associated with the farmers' reduced independence on becoming irrigators
- Problems of soil suitability and soil variability

DESIGN AND CONSTRUCTION STAGE FLAWS

- Inadequate design, requiring subsequent major changes
- Poor on-farm development
- Inappropriateness of imposed cropping calendars

OPERATION AND MANAGEMENT DIFFICULTIES

- Poor management of irrigation agencies (government departments)
- Problems involved with the management and maintenance of irrigation technology
- Poor distribution of water within the scheme
- Poor on-farm water management
- Inadequacy of extension services
- Public health problems
- Problems of salinisation and water-table rise, necessitating costly drainage and reclamation strategies
- Poor level of involvement by farmers

FINANCIAL/ECONOMIC PROBLEMS

- Very high development costs per hectare
- Inadequate importance attached to funding of post-construction activities
- Heavy costs and low level of performance of irrigation agencies
- Difficulties of collecting water charges

Source: Hotes, 1982; van Steekelenburg and Zijlstra, 1985; World Bank, 1979

irrigation (SSI). In the UK the Small-Scale Irrigation Working Group comprises over 100 consultants, researchers and academics who meet (generally 30-40 on any occasion) for its regular biannual meetings. The International Irrigation Management Institute (IIMI) has an active research, publication and networking programme in Farmer Managed Irrigation Systems (FMIS). Both these groups have as their aims the understanding and promotion of a form of irrigation development which emphasises the farmer's role in management and which of necessity therefore involves small units of production. This emphasis represents a radial departure from previous practices, as is shown in Figure 1 (for definitions of terms, see Annex p. 113).

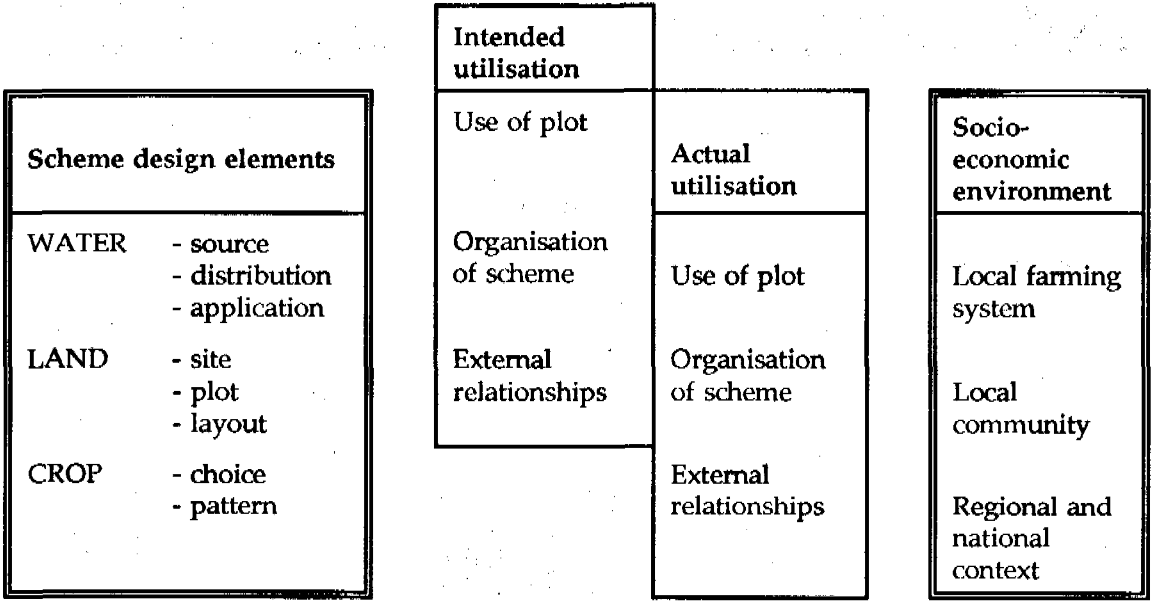
The current debate is constructive and helpful for a number of reasons. Firstly, because it transcends the sterile confrontations (especially between engineers and sociologists) of earlier years, in particular by attempting to build bridges between disparate disciplines; secondly, because it is producing genuinely new and promising approaches to development practice; and thirdly, because it is able to contribute ideas to the management and rehabilitation of schemes constructed in the old-fashioned 'top-down' style which, though far from ideal in conception, represent major investments which must therefore be made to work if possible.

Top-down smallholder irrigation development: an obsolete approach

The inappropriateness of past approaches to irrigation development in sub-Saharan Africa is becoming more widely accepted. It is recognised that past perceptions of the role and place of irrigation in the farming system have led to unrealistic expectations about how irrigation schemes would be managed and operated, and about the benefits which would follow.

Figure 2 (from the Proposal for the Training Course 'Design for sustainable Farmer-Managed Irrigation in sub-Saharan Africa', by Wageningen Agricultural University, Institute of Irrigation Studies and Silsoe College) shows the mismatch which often occurs between the intended and the actual operation of an irrigation scheme.

FIGURE 2
Mismatch between intended and actual operation of an irrigation scheme



A new approach to irrigation development in sub-Saharan Africa is necessary. This approach should be:

- farmer centred
- truly inter-disciplinary
- characterised by dialogue, interaction and flexibility.

These characteristics and their implications are developed further below. They are at the core of what has come to be called Small-Scale Irrigation (SSI).

THE DANGERS OF OVER-REACTION

As with any radical change in approach, there are dangers: the dangers of wholesale rejection of previous practices and standards, and the risks associated with unthinking commitment to the relatively unknown.

Perhaps the most common mistake among non-specialists is to ignore the complexity of small-scale irrigation development. Talk of 'small scale', 'low technology', and farmer-management' can give an impression of delightful simplicity, especially when set against the detailed and multi-disciplinary studies involved in the preparation of large irrigation schemes. On the contrary, small-scale irrigation does not escape any of the complexity of irrigation in general. Indeed because of its scale and its inherently less predictable nature, some aspects of SSI are actually more difficult to handle than the corresponding aspects of large scale schemes. To indicate the nature of this complexity Figure 3 sets out the major issues and subjects which have to be addressed in the design of any public irrigation scheme be it large or small.

In implementation, likewise, the development of small-scale irrigation may not be able to support the wide range of expertise and technical input available to large and costly enterprises. A single engineer may now need sufficient economic, agronomic and management know-how, as well as engineering skill, to combine a number of roles. This presents difficulties for current approaches to training and education, but it does have the major advantage of creating an interdisciplinary professional mentality more akin to that of the farmer than to that of the narrow subject specialist.

Thirdly, the importance of quality (in survey, design and construction especially) needs emphasising. A stress on 'low' technology and low-cost works need not, and should not, mean compromises over quality. Surveys should be accurate, designs should be competent, and construction quality should be managed to a high level, all within the constraints of budgets which reflect the real level of benefits achievable.

Lastly, in the reaction from 'top-down' approaches and in the current fashion of respect for 'indigenous technical knowledge', it is possible to have an over-romantic image of the farmer. We are right to arrive at a deep respect for the farmer's expertise in survival and risk-spreading, and in his knowledge of the land and the crops it can support; but this respect must be tempered by the recognition of the rainfed farmer's areas of ignorance. He probably has little innate understanding of on-farm water management, he may have little experience of organised group activities (such as channel maintenance), and many aspects of agricultural intensification will be new to him. Indeed, ideas of crop responses to water developed under rainfed conditions may lead to problems such as gross over-irrigation.

PRODUCTION VERSUS SOCIAL DEVELOPMENT: THE DILEMMA OF SMALLHOLDER IRRIGATION PROJECTS

It is the hypothesis of this writer that there is often a fundamental incompatibility between the objectives of national governments in promoting irrigation development, and the aims and aspirations of small farmers. Government objectives may include social development (rural employment, increased incomes, improved nutrition and public services) but their primary aim is usually in terms of increased production, often of specific crops (e.g. rice, wheat, sugar), and often to substitute for imports. On the other hand, developing country farmers may be less interested in putting all their eggs in the one basket of intensified production of a specified crop or crops, and more concerned to reduce risks through diversifying their food production and income-generating activities.

If these two sets of aims can come together in a single scheme, then success may follow; however, it seems more common than not (at least in Africa) that they do not. Conventional design procedures for smallholder irrigation embody many assumptions about farmers' aims, and about their willingness to take part in this form of development. Reality has shown the error of these conventional top-down approaches.

FIGURE 3
Checklist of issues and subjects to be addressed in the planning and design of any public irrigation scheme

PRESENT PRACTICE AND POTENTIAL FOR IRRIGATION

- Present farming system and household economies
- Farmers' interest in irrigation development
- Present land tenure arrangements
- Existing water rights and practices
- Likely impact on women and disadvantaged groups of irrigation development
- Other socio-economic impacts on non-participants
- Soil suitability
- Water resources and technical potential for exploitation
- Crop suitability
- Labour availability
- Requirements for crop storage and processing
- Existence of, and access to, markets

DESIGN DECISIONS

- Method of water abstraction and conveyance
- Method of water application
- Farm/plot size and field layout
- Labour needs and farm power requirements (mechanisation)
- Proposed operating procedures
- Role of women in proposed scheme

FINANCIAL AND RELATED ASPECTS

- Level of, and method of recovering, water charges
- Provision of credit
- Mechanisms for input supply

OPERATION, MAINTENANCE AND MANAGEMENT

- Roles of farmer associations/water user groups
- Roles of government agency/NGO
- Organisation of maintenance activities
- Organisation of water requests and supply procedures
- Provision of extension services

ENVIRONMENTAL IMPACT

- Impact of irrigation on public health
- Impact on water quality
- Effect on water-table
- Effects on downstream water users

It may well be that in regions with little experience of irrigation the attempt to combine production objectives with social development objectives should be abandoned. If the aim is production, then the estate/plantation/commercial sector is the right arena. If the aim is social or rural development, then (small-scale) farmer managed approaches may fit better. There is no good reason why smallholder irrigation projects targeted at former rainfed producers, who have complex farming systems and diversified household economies, should be expected to work.

There is a major difference between the background just painted of much of rural Africa and the situation of strong traditional rice irrigation economies in Asia; in the latter case smallholder schemes are really water supply schemes to supply an existing activity, rather than involving a radical shake-up of the farming system and rural economy. This arguably is the pattern which government irrigation agencies elsewhere should follow.

ROLE OF IRRIGATION IN POVERTY ALLEVIATION AND SOCIAL AND ECONOMIC DEVELOPMENT

If then the production objective is best met through private sector commercial enterprise, what role can irrigation development play in social and rural development? Is irrigation a useful vehicle for delivering wider developmental benefits, including those of poverty alleviation and food security, or are its associated problems and costs simply too great, as Moris (1987) has suggested in referring to irrigation as a "privileged solution"?

The World Bank (Barghouti and Le Moigne, 1990) still appears to view irrigation primarily as a means of increasing production, and of course without production benefits (including both increased production and more reliable production) then no other benefits are likely to accrue. The questions are; production of what, for whom, and under whose control?

Evidence is widespread that, under the right conditions (of relative autonomy in crop selection and production, ready access to markets and attractive prices) farmers will benefit from irrigation facilities. The precise ways in which they benefit are not always easily predictable. For example, a recent programme of studies (Diemer and Huibers, 1991) in Senegal showed that successful village-level irrigation schemes were used by farmers not to increase significantly production for market (as might have been expected), but rather to reduce hot-season farming activities and to permit them to pursue other income-generating activities at this time of year: in other words, to reduce risks and take advantage of greater opportunities for diversification. In Nigeria, on the other hand, the more attractive wheat price since 1988 has stimulated private small- and large-scale (irrigated) production in a way that 40 years' of conventional smallholder irrigation development failed to do (Kimmage, 1991).

Irrigation development can provide a real contribution to rural social development in two main ways, and under a number of conditions:

- through assistance provided to existing (traditional) irrigators
- through the introduction of irrigation to former rainfed producers or to those who were not previously involved in crop production.

The first of these is the easier although it has its own pitfalls. A major reason why Asian irrigation development has, on the whole, been more successful than that promoted in Africa is that the beneficiary farmers have already been practising some form of irrigation or water management (usually for paddy production), often for generations. But in Africa too, where Governments and NGOs have sensitively addressed some of the difficulties or bottlenecks experienced by existing (traditional) irrigators, results have been promising. Examples of such interventions can be found for example in the northern Nigerian fadamas, in Burkina Faso and in Zimbabwe (Carter, 1989) as well as in Nepal, Bhutan and Thailand. Interventions need not and arguably should not be comprehensive, but may address a single issue such as water lifting, water control or water conveyance.

The more difficult situation is where the attempt is made to introduce irrigation to farmers who have no previous experience. The enormity of the step from pastoralism or rainfed production to irrigation is easily under-estimated, and it is here that many well-meaning attempts to provide assistance have come adrift. The main problems, apart from the farmers' lack of technical know-how in water management, relate to the intensification of farming that goes with irrigation (and so the need for the farmer to learn many new skills at once), and the inevitable loss of independence which accompanies most forms of irrigation activity. The argument for improving rainfed production first, before introducing irrigation, is very strong. Figure 4 lists the major ways in which this may be done. When irrigation development is further complicated by resettlement, and the consequent disruption of existing social structures and infrastructure, the task can become even more problematic.

FIGURE 4
Possible improvements to rainfed agriculture as a precursor or alternative to the introduction of irrigation (after van Steekelenburg and Zijlstra, 1985)

- Improving or organising reliable market outlets
- Developing improved varieties of the traditional crops that are higher yielding but yet low in their demands for fertilizer, pesticides and water
- Ensuring a timely supply to the farmers of all the inputs required to obtain high production levels (quality seed, fertilizer, spare parts, etc.)
- Improving the quality and capacity of facilities for crop processing and storage so as to reduce post-harvest losses
- Recommending better agricultural production techniques, such as better land preparation and crop rotation or crop mixes
- Improving the quality and motivation of agricultural extension staff to transfer the information on production techniques
- Improving credit facilities: for the short term, perhaps in conjunction with traditional money lenders (harvest-anticipating credit); for the medium term, through Government or private banks
- Improving the transport infrastructure and the means of transportation
- And last but not least, offering prices that are an incentive to farmers to increase production.

CONDITIONS FOR SUCCESSFUL SSI

In the previous section reference was made to the conditions under which irrigation development could make a real contribution to rural and socio-economic development. The experience and reflection of the last 15 or so years - the SSI era - allows us to summarise at least some of these conditions and to identify areas where further understanding is needed.

- The first condition for farmer-centred irrigation development to succeed is the coincidence of farmer aims and objectives with those of any agency (government or NGO) providing assistance. A mismatch here spells disaster. Too often government irrigation policy and strategy are couched in terms too vague to be clear on this point, and in any case insufficient time is spent in dialogue with farmers to ascertain their own aims. Much of the most successful irrigation in Africa has been developed by farmers without the intervention or interference of Government agencies; in these circumstances the conflict of objectives highlighted above has not arisen.

- The second necessary condition is farmer autonomy. Producers should either be permitted to behave as farmers, who make their own decisions on cropping calendars and who manage their own farming systems, or they should be employed as wage labourers. In either case their position is clear. In many (African) smallholder projects farmers are such in name only, when virtually all autonomy is taken from them.

- The third condition is that the technology and physical systems supplying irrigation water must be able to be operated and maintained (within farmers' own budgets) without heavy dependence on unreliable supply and service agencies. The VLOM (Village Level Operation and Organisation of Maintenance) concept of village drinking water supply (Arlosoroff *et al.*, 1987) is highly relevant to the case of small-scale irrigation.

- The fourth condition is that agencies (government or NGO) providing technical or other assistance in irrigation should take a support role rather than a dominant part. Their role should be to assist farmers in their own development, not to impose a particular pattern of 'development' on them.

- The fifth condition, which is implicit in the first four, is best expressed by Diemer and Huibers (1991) on the basis of their work in Senegal. It is a condition which must be reflected in the attitudes and approaches of irrigation agencies, and which has important implications for the whole process of intervention. "The most important conclusion ..... is the need to recognise that the irrigator's economic and social circumstances are just as important for viable irrigation development as the physical conditions. These circumstances have to be reflected in any irrigation design. Schemes based on desirable behaviour patterns imposed from above are almost bound to fail."

These five conditions should no longer be controversial although they are by no means universally observed in practice. There is still a major task ahead to establish these basic tenets as accepted orthodoxy. Although directions are becoming clearer, there is still much to learn about what can work and what cannot work in irrigation development. The needs for R&D in small-scale irrigation fall under three broad headings (Carter, 1991). Firstly there is a need for increased understanding of both the technology and the social organisation of traditional irrigation systems; secondly there is the need to develop improved approaches to design of new farmer-managed systems, particularly taking a lead from the excellent work of Wageningen Agricultural University (e.g. WAU, 1990); and thirdly there is the need to develop and change the approaches of irrigation professionals, institutions (both government and NGO), and funding bodies.

IMPLICATIONS OF THE SSI PHILOSOPHY

Project conception and assessment of irrigation potential

The first major implication of the new approach relates to the identification of 'irrigation potential' and of specific projects. Conventional wisdom has made the simplistic equation that suitable soils plus exploitable water adds up to irrigation potential. Organisations such as FAO (Thomas, 1987) and the World Bank (Barghouti and Le Moigne, 1991) have perpetuated this myth by failing to allow for the human element. Suitable soils and available water are necessary, but by no means sufficient, conditions for irrigation development since the success of farmer irrigation depends crucially on many factors other than the accepted technical and economic feasibility criteria (Figure 5).

Of course this new realism makes the identification of irrigation potential much more difficult and far less predictable; but present approaches to this subject can at best give only extreme upper bounds to the potential for development.

FIGURE 5
Two paradigms of the concept 'irrigation potential'

THE SIMPLISTIC MYTH

- Suitable land + Proximity to water = Irrigation potential

A CLOSER APPROXIMATION

If the following apply:
- water supply is a major constraint to production *and*
- soils are suitable *and*
- water and affordable, maintainable water delivery technology is available *and*
- farmers wish to irrigate *and*
- appropriate farmer and/or Government organisations for water management exist or can be developed *and*
- appropriate levels of mechanisation are available and viable *and*
- inputs - fertiliser, seed, pesticides - are available *and*
- credit for input supply is available *and*
- crop prices are attractive *and*
- markets are accessible *and*
- issues of land tenure and water rights have been satisfactorily resolved *and*
- proposed irrigation activities are environmentally sustainable

then irrigation development may be a viable option

Design and construction

The implications for scheme design have been particularly highlighted by a number of workers at Wageningen Agricultural University in the Netherlands. They have pointed out two key aspects of a new design process. Firstly, the willingness on the part of the designer to question conventional wisdom about human behaviour (in other words to identify how farmers will actually utilise and benefit from irrigation facilities provided); and secondly, the need to carry out the design process interactively, with farmers' views and wishes in relation to scheme location, site layout and other aspects of design being respected as fully as possible. These two aspects alone represent a radical departure from conventional engineering design practice.

Other aspects of design and construction, such as the use of local materials and construction skills, and selection of field layouts to suit land levelling practices which are readily available, are fairly obvious. The principle of 'design for (farmer-) management' is fundamental and this too requires professionals with field experience not merely office skills.

Operation and maintenance

The imperative of farmer control of operation and maintenance is not merely for the reasons outlined earlier in this paper. There is a pragmatic imperative too. Increasingly Governments are recognising their own inability, for financial or other resource reasons, to manage and maintain an increasing acreage of irrigated agriculture. Were it not for the widespread philosophy of disengagement, turnover or privatisation, there would be a real danger of irrigation becoming one of Moris's (1987) "privileged solutions" (strategies which seem so obviously right as to need little justification and which therefore win priority access to funding).

Institutional roles

The institutions involved in the promotion of irrigation need to evolve new roles and attitudes.

- Government agencies need to develop approaches which give greater respect to the knowledge, skills and wishes of farming communities; and irrigation professionals, particularly engineers, need to develop a more farmer-centred orientation.
- NGOs, while generally having strengths in the community-based approach of SSI, often lack rigorous technical expertise. They must be prepared either to buy in such know-how or develop it themselves.
- Donors will need to come to terms with far less cut-and-dried project formulations, since the SSI approach demands more flexible funding arrangements and timetables. Donors should require evidence of full farmer participation in proposed irrigation developments.
- Educational and training institutions should make greater efforts to bridge the divide between social sciences and the agricultural and engineering studies needed for irrigation development. Narrow subject specialisms are inappropriate in this field.

Focus for action

Four major areas emerge in which 'outsiders' (Government, donors and technical assistance) may have a role:

- *Traditional Water Management and Irrigation Practices*: The priority here is to identify, quantify, evaluate and understand. Too often 'modern' irrigation development has supplanted well managed existing agricultural practices which have been ignored or overlooked in the urge for progress. A true value should be placed on such 'traditional' systems of crop production.
- *New Development*: Here the need to develop new interactive design procedures, and the consequent requirements for training are key.
- *Existing Smallholder Schemes*: This area needs attention. Better provision of support services, assistance in turnover processes, and a fundamental re-think about processes of rehabilitation are needed here.
- *National Irrigation Development Policy*: Arguably, the fundamental area is discussed in the next section.

A KEY ROLE FOR TECHNICAL ASSISTANCE: POLICY DEVELOPMENT AND STRATEGY FORMULATION

The key area is that of national irrigation development policy. In any particular country or region the roles of irrigation need to be defined, and the options and priorities for intervention need to be spelled out. In most developing countries, and especially in Africa, SSI should be an important component of such policy (alongside existing large-scale smallholder schemes and the commercial sector). Formulation of strategies in pursuance of such policies can then follow. Models for such strategy formulation can be found in the work on irrigation manpower planning by Carter *et al.* (1986) and Carter and Mason (1988) and in that of Morris and Bishop (1989 and 1990) and Bishop (1990) on agricultural mechanisation.

It is essential that policy development and strategy formulation are carried out by the responsible national Governments, not by outsiders. Nevertheless, external technical assistance may be necessary to expose policy makers to the options and to give them the opportunities to consult widely as they develop their own approaches.

It is particularly important that younger irrigation professionals are exposed to the new approaches to irrigation development. This should be by a combination of in-country training and, where appropriate, on international training programmes.

IRRIGATION DEVELOPMENT IN SUB-SAHARAN AFRICA: A SUMMARY OF PRIORITIES FOR DONORS

The following list suggests key ways in which donors can assist in the promotion and support of irrigation in the region:

- Continuation and communication of results of sector evaluations
- Interdisciplinary research on all types of scheme/system
- Quantification and valuation of traditional practices
- Research on alternatives to irrigation and alternative approaches to irrigation
- Assistance in policy/strategy formulation
- Co-ordination with other donors/lenders
- Support to NGOs
- Support to commercial sector
- Rehabilitation.

ANNEX

Definitions

Definitions adopted by Underhill (1984) and UK SSI group:

Formal irrigation: Formal irrigation is the development and management of irrigated agriculture in a structurally formal way, usually by a government body. [Such schemes] are often established with very little prior involvement from farmers or landholders; and are usually managed by a structured government organisation on behalf of the resettled smallholders.

Small-scale irrigation (SSI): Small-scale irrigation, usually on small plots, in which small farmers have the major controlling influence, and using a level of technology which the farmers can effectively operate and maintain.

[Note this SSI concept and IIMI's Farmer Managed Irrigation Systems (FMIS) are identical]

Scale: For Africa, FAO has adopted the following scheme size classes for smallholder irrigation projects: FAO 1987, quoted in Underhill (1990).

1. Very large-scale schemes: typically over 10 000 ha with full water control and under government management. Examples are the gravity schemes in the large river basins in Sudan (Gezira), Morocco (Gharb) and Egypt

2. Large-scale schemes: typically 1000 to 10 000 ha with full water control. Generally under government or commercial management, the latter usually less than 5000 ha. Examples are found in Kenya (Bura; Mwea), Tanzania (Mbarali), Somalia (Shebelli)

3. Medium-scale schemes: typically 100 to 1000 ha with full or partial water control. Government managed, government assisted cooperatives, or commercial estates

4. Small-scale schemes: typically 1 to 100 ha controlled by farmers; groups, or single farmers. Examples are: Kenya, Zimbabwe, Tanzania, Madagascar for simple river diversions, Nigeria (fadama) for shallow groundwater, and Kenya, Tanzania for pumping from lakes

Note: To these four classes of irrigation 'schemes' could be added irrigated 'garden plots' from a few square metres to perhaps 0.5 ha in size, controlled by single farmers and usually based on shallow groundwater. Examples are found all over Africa. (The term 'micro irrigation' is sometimes used for garden plots but should be avoided as the International Commission on Irrigation and Drainage recommends that this term be used for the technologies of 'localized irrigation' such as trickle and drip (see FARO 1980c).

(Note the links between scale and management)

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DISCUSSION

In the discussion a recent ODA/NGO seminar on popular participation projects was referred to. The difficulties of multiplying up small-scale projects was mentioned as well as problems in accounting for process type projects because firm programmes, targets and costs cannot be prepared in advance. Opinions differed as to whether donor assistance should be to small- or large-scale projects. However, emphasis should be on rehabilitation based on the tenets of SSI experience in large schemes. Donors should support NGOs and local banks for provision of credit rather than major commercial lending. It was suggested that ODA should reduce irrigation spending by 25-40% in view of the changing demographic situation but it was pointed out that some donors are increasing their rural-based activities to discourage rural migration. It was said that 35-40% of Asian agricultural land is irrigated, producing 60-70% of food grains and that this is from both small- and large-scale developments. So the distinction should be more between well- and ill-conceived projects rather than between small- and large-scale projects. The question was posed as to what countries such as India and Pakistan should do without irrigation; the carrying capacity of rainfed land in Pakistan is no more than 5% of the total population. Finally, concern was expressed at the speed with which the management of irrigation schemes is being handed over in some countries. In many cases, this necessitates a sudden switch after many years of highly centralised and top-down management to water users' groups which have hardly developed in any meaningful sense.

PAPER 12

Environmental and health aspects of irrigation

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Summary: The paper shows how awareness and understanding of the relationship between human activity and environmental change have developed over the last 20 years with regard to irrigation in developing countries. The terminology of 'impacts' and of 'sustainability' are examined in relation to irrigation projects and to the wider environment, resources and societies within which they are located. From this discussion various key issues are identified concerning the environmental impact and sustainability of irrigation systems. These have implications both for policy formulation and research. The paper ends by examining the difficulties of research in such inter-disciplinary subject areas using projects undertaken by the Overseas Development Unit at HR Wallingford by way of example.

THE RISE IN ENVIRONMENTAL CONSCIOUSNESS AND CONFLICT IN IRRIGATION AND WATER RESOURCES DEVELOPMENT

The Overseas Development Unit (ODU) of HR Wallingford (formerly the Hydraulics Research Station) was established in 1973 to provide specialist expertise and undertake research on behalf of the Engineering Division of the ODA in problems of water resources and irrigation in developing countries. The ODU endeavours to ensure that its research programme addresses the water resources and irrigation problems considered most acute, at a particular time, by practising engineers in developing countries and specialists and aid officials from the UK. Surprisingly the term 'environment' does not feature in the title of any ODU research project prior to 1987 (An investigation of schistosomiasis control in irrigation schemes, begun in 1983, was later given an 'environmental' title). By contrast, the current (1992/93) programme groups approximately one third of the Unit's work under a theme 'Environmental Effects'.

The deduction from this, that the environment was not an important consideration until approximately five years ago in the perception of most Third World irrigation and water-resources engineers and researchers would, however, be misleading: although key terminology and concepts were absent, the processes were under active study. For example, one of the projects on which the ODU started its research 19 years ago was a study of salinity (sea water) intrusion in tropical estuaries. This phenomenon, resulting from freshwater abstraction and the regulation of river flows particularly for irrigation, has major environmental implications. The types of numerical modelling technique developed in that early project remain invaluable as part of the tool-kit used by engineers in seeking to understand, predict and manage environmental change in tropical river basins. Undoubtedly this project would legitimately be included as part of the 'Environmental Effects' theme if it were part of the ODU's current research programme. Similarly, studies of catchment erosion and soil salinisation which have featured in the ODU's research for many years are now regarded as 'environmental' issues.

On the same basis, almost every other project on which the ODU has been engaged over the last 19 years could be considered as having an important bearing on 'the environment'. This is hardly surprising when one considers that irrigation is a process which involves interactions between almost every facet of the environment: atmospheric gases, water, soils and minerals, energy, biological species and communities and human activities and relationships.

Yet vocabulary and concepts relating to 'the environment' have, as noted above, assumed importance only relatively recently in irrigation and water resources development. Unfortunately this change has arisen for largely negative reasons as a result of the publicity given to particular water resources projects which have been built without adequate consideration for their overall and long-term effects. In response to this, the techniques of Environmental Impact Assessment were developed and, in many countries, enforced through legislation in order to prevent projects from proceeding if they were likely to cause adverse environmental impacts. This inevitably created a situation of conflict between engineers and planners on the one hand and environmental specialists and 'conservationists' on the other over the implementation of new projects; disputes which led to severe delays and, in some cases, to the cancellation of projects which may have taken many man-years of planning and design. Such conflicts came as a psychological shock to many engineers who had previously believed that their's was a profession which was entirely and self-evidently serving the needs of society.

THE BASIS FOR FUTURE CO-OPERATION

Situations of conflict and inertia as described above are beginning to give way to a realisation that the traditional roles of engineers and other professional groups are changing and that closer co-operation is needed to address the complex issues which we face in seeking to optimise decisions concerning the future development of water resources and their impact on the environment. However, considerable progress must first be made in clarifying concepts, in developing a broader understanding and new ways of working and in evolving new technical skills. The principal needs, as I see them, are discussed below.

To develop a clearer understanding of 'the environment'

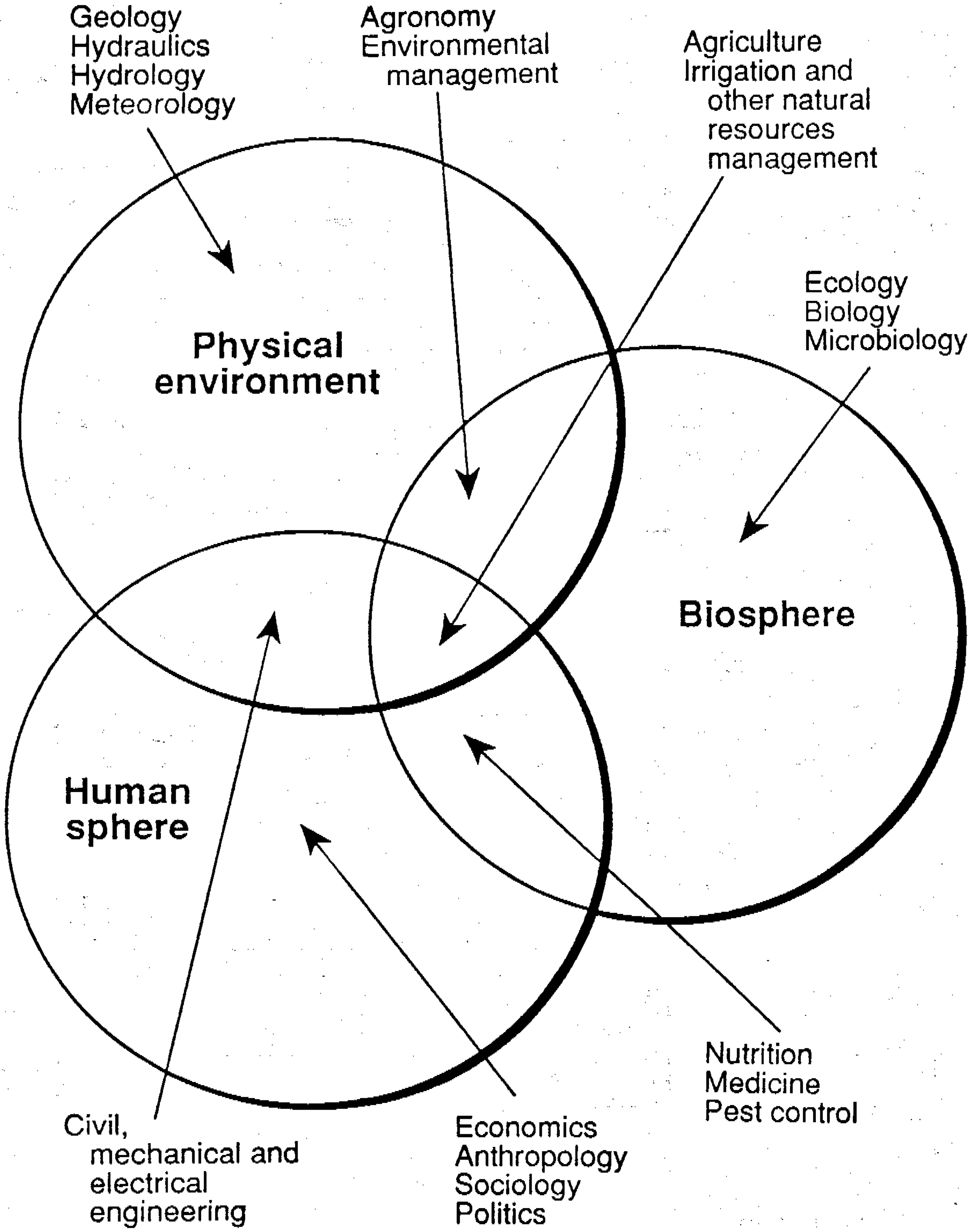
One source of confusion in considering 'environmental effects' is the different shades of usage which are given to the term. Often when examined closely, the intended meaning is restricted to effects related to wildlife and natural ecology. The use of the term 'environmental effects' to refer primarily to ecological changes accords with the increasing concern about 'conservation' in 'industrialised' countries which have already undergone substantial social and land-use changes and where the most common and far-reaching effects of current water-related activity are changes to water quality affecting wildlife. By contrast, in most tropical developing regions physical changes to the environment and changes which affect society are equally, if not more, important than the biological changes. It is, therefore, necessary to ensure that in discussions concerning 'environmental' effects the physical, biological and social aspects are each considered in full (see Figure 1).

In the remainder of this paper the combined interactions of the human, biological and physical spheres will be intended whenever the terms 'environment' or 'environmental' are used. In this usage, they are synonymous with such words as 'comprehensive', 'global', 'holistic'. This meaning, which links with the development of EIA procedures, carries the connotation 'everything we can possibly think of which might be influenced by or influence the activity under examination'. This is the meaning envisaged by the Environmental Impacts Working Group of the International Commission on Irrigation and Drainage (ICID) when it drafted a Check-list of possible environmental impacts (see Figure 2).

A further step towards clarification of terminology is suggested by the phrase "might be influenced by or influence". A distinction can be drawn between those effects which the environment has on the project and those which the project has on the environment. The merit of stressing this distinction is that it ensures that a project planner, designer or manager is assigned the full responsibility for all factors which affect the primary productivity of the project. Effects such as sedimentation, soil salinisation, social, financial or organisational problems and agricultural weeds and pests cannot be pushed to one side as 'environmental impacts' simply because the person responsible for the project does not know how to deal with them. Such effects must be considered to ensure that a project's primary productivity will not decline with time.

In this respect, the relatively recent introduction of the term 'sustainable' development is particularly helpful. Rather than talking in terms of the impact of the environment on a project, the question "is the project sustainable?" clearly places the responsibility for ensuring that such effects are considered on the person responsible for the project. For practical purposes, this

FIGURE 1
Examples of disciplines relating to the major components of the environment associated with irrigation



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question may be sub-divided into separate questions concerning the resources on which the project depends. The first part of Table 1 lists the separate resources and illustrates how concern over impacts (e.g. salinisation) translates into questions of sustainability (in that case, sustained soil fertility). Thus, with respect to the effects of the environment on the project the term 'sustainability' provides a better framework for guiding the project official than does the term 'impacts'.

FIGURE 2

ICID Check-list of possible environmental impacts of irrigation, drainage and flood-control projects

Hydrology	1-1 Low flow regime	
	1-2 Flood regime	
	1-3 Operation of dams	
	1-4 Fall of water table	
	1-5 Rise of water table	
Pollution	2-1 Solute dispersion	
	2-2 Toxic substances	
	2-3 Organic pollution	
	2-4 Anaerobic effects	
	2-5 Gas emissions	
Soils	3-1 Soil salinisation	
	3-2 Soil properties	
	3-3 Saline groundwater	
	3-4 Saline drainage	
	3-5 Saline intrusion	
Sediments	4-1 Local erosion	
	4-2 Hinterland effect	
	4-3 Sediment yield	
	4-4 River morphology	
	4-5 Channel regime	
	4-6 Sedimentation	
	4-7 Estuary erosion	
Ecology	5-1 Project lands	
	5-2 Water bodies	
	5-3 Surrounding area	
	5-4 Valleys & shores	
	5-5 Wetlands & plains	
	5-6 Rare species	
	5-7 Animal migration	
	5-8 Natural industry	
Socio-economic	6-1 Population change	
	6-2 Income & amenity	
	6-3 Human migration	
	6-4 Resettlement	
	6-5 Women's role	
	6-6 Minority groups	
	6-7 Sites of value	
	6-8 Regional effects	
	6-9 User involvement	
Health	7-1 Water & sanitation	
	7-2 Habitation	
	7-3 Health services	
	7-4 Nutrition	
	7-5 Relocation effect	
	7-6 Disease ecology	
	7-7 Disease hosts	
	7-8 Disease control	
	7-9 Other hazards	
Imbalances	8-1 Pests & weeds	
	8-2 Animal diseases	
	8-3 Aquatic weeds	
	8-4 Structural damage	
	8-5 Animal imbalances	

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TABLE 1
Selected items to illustrate the links between impacts and sustainability

	Project-related effects		Wider effects	
Resource	Impacts on the project	Considerations for sustainability	Impacts on the environment	Considerations for sustainability
Water	Water shortages Floods Sedimentation Pollution	Protected water source Water management Flood protection Sediment control	Downstream hydrological and morphological changes	Surface and groundwater resources Sediment management
Land/ Mineral	Salinisation Sedimentation Waterlogging	Soil fertility Catchment management Drainage	Land degradation Hinterland effects	Drainage water and groundwater Fuelwood and grazing provision
Biological	Weeds and pests	Crop ecology	Loss of species Loss of habitat	Genetic diversity Aquatic and terrestrial ecology
Human	Lack of skills Mismanagement Lack of credit Lack of markets	Financial and institutional factors	Health Resettlement Social conflicts	Disease ecology Social, economic and political factors
Other (energy, etc.)	Fuel shortages	Energy provision	Global warming	Gas emissions

The extent to which the project official carries responsibility for wider environmental effects depends to some extent on the institutional framework which exists. Such effects might also be viewed in terms of 'sustainability', as shown in the right-hand columns of Table 1, but it would generally be the responsibility of a higher authority such as a river basin authority or environmental protection agency, rather than the project official, to ensure that individual projects do not compromise the sustainability of these regional, or even global, resources and systems. If competent authorities do exist at this higher level, the official responsible for an individual project can treat wider environmental effects as 'impacts' of his project whose nature he/she must attempt to specify but whose implications the higher authority has the responsibility to assess. Thus the terms of 'impacts' and 'sustainability' may both have a role to play depending on the particular context.

Unfortunately in many situations in developing countries institutional responsibilities may not be clearly defined and a project official may not be in a position to pass to others the responsibility for considering how the sustainability of wider environmental systems is affected by the project. In such cases the above attempt to clarify the terminology may not be relevant and the project official may find he/she has responsibility for impacts which are more far-reaching than he/she has resources to assess.

To understand the special circumstances relating to tropical developing regions

There are substantial differences between temperate (industrialised) and tropical (developing) countries with regard to the environmental effects associated with irrigation and water resources development. It has already been mentioned that the main environmental preoccupation in 'western' countries tends to be the effect of water quality changes on wildlife. In the Third World this is only one of several major environmental changes which are occurring alongside or as a result of irrigation and water resources development. The reasons for the wide range of factors to be considered include :

- a greater intensity, seasonality and variability of rainfall leading to high rates of erosion and geomorphological activity and the need for substantial reservoir storage capacity
- higher temperatures leading to higher rates of evaporation and hence higher crop water requirements and also to greater productivity and diversity of ecological systems which in turn cause increased problems of human disease and crop pests
- higher population growth rates leading to increasing demands for agricultural land and for irrigation, domestic and industrial water
- weaker economies and a poorer population leading to problems of poverty-related disease and environmental degradation as well as intense competition for capital which results in the desire for cost savings (for example, by the omission of drainage works) which have long-term environmental repercussions
- social, political and institutional systems which are less capable of coping with the conflicts which arise in resource allocation and environmental management, conflicts which the projects themselves may generate
- relative scarcity of the technical and managerial skills needed to predict and manage environmental change.

Considering the above differences in relation to the scope of environmental effects defined in Figure 1, it is clear that a vast amount of skill, knowledge and experience would be needed to 'manage' the environmental changes associated with irrigation if it were to be undertaken with the thoroughness and confidence that is implied by those who call for improved environmental management.

Throughout the remainder of the paper I shall try to highlight practicable ways in which progress can be and is being made, albeit slowly, in the areas of environmental management with which I am most familiar. My starting point is always to consider how to assist the existing professional staff, many of whom are engineers like myself, to broaden the scope of their activities and understanding, with respect to identifying and managing more effectively environmental change, given the severe constraints and conflicting demands which characterise their situation.

To address the key issues

The central issue with regard to future irrigation development, an issue which is of growing importance for the environment, is the impact of the consumption of water for irrigation on surface water and groundwater resources and hence on other human water users and on the physical and ecological characteristics of the terrestrial areas and water bodies depending on these resources. Irrigation is man's most significant consumptive use of water with typically a depth of between half and one metre of water being evaporated from every topical irrigated field during the growing period of a single crop. During the process the sediment and dissolved solids (salts and pollutants) previously carried by the water are left behind either through deposition (resulting in sedimentation or salinisation) or by causing increased concentrations in the water which remains. Apart from the evaporated water, some of the water diverted for irrigation will percolate into the ground where it may result in a progressive rise in water-table and eventual waterlogging. These processes are, therefore, the source of several major types of environmental impact and the cause for a lack of sustainability in many individual projects. Moreover, irrigation's high consumptive use of water is likely to feature as an increasingly important cause for water shortage and hence conflict in the overall management of water resources.

For the above reasons, water-use efficiency (the productivity of a unit volume of water in terms of the amount of crop it produces) is becoming a key parameter in irrigation planning and management. In the first analysis it can be assumed that if water-use efficiency can be improved, the overall environmental impact of irrigation will be reduced. There are a number of practical ways in which possible improvements in efficiency can be sought: from the purely physical (improved canal linings and seepage reduction, software to assist the scheduling of irrigation releases, micro irrigation and sprinkler techniques); to the biological (alternative crops or varieties); and human aspects (institutional, managerial and financial factors). Work on each of these is progressing in various institutions in the UK and around the world. They are important but by themselves they are not enough to ensure reduced environment impacts. This is why I used the phrase "in the first analysis" when referring to the importance of water-use efficiency in relation to environmental effects.

Unfortunately there are other interlinking factors which are environmentally significant and must also be considered. For example, to achieve the highest possible crop yields for a given volume of water is likely to entail the use of agrochemicals. These introduce both a direct financial cost as well as an environmental cost in terms of pollution. Likewise high water-use efficiencies may be environmentally harmful if low rates of water application lead to progressive accumulation of salts in the soils and consequent loss of soil fertility. As a further example, some crops which are highly productive in terms of water use may demand high levels of farm labour or mechanisation or require post-harvest processing which have possible social and pollution implications.

Two aspects of environmental change which relate less closely than most to the efficiency of irrigation water use are the ecological impacts and the social impacts (including health impacts). In many instances, the attempt to increase the 'efficiency' of exploiting natural resources inevitably leads to a loss of species diversity and 'poorer' ecosystems. This is true in an irrigation scheme where large tracts of land are converted to monocropping and the creation of 'managed' canals and reservoirs provides only limited support for aquatic life. Modified operation of existing schemes to achieve less 'wasteful' use of water may also lead to the drying out of wetland areas which had previously been rich in wildlife. (However, in relation to human health, the opposite is generally true: for example, high water-use efficiency is likely to produce fewer water bodies suitable for colonisation by the vectors or hosts of human parasitic diseases.) In other respects, social impacts often bear little relation to the efficiency of water use: resettlement, which in many countries is one of the most contentious issues, relates to the land area under development, not the water use.

Thus, whilst high water-use efficiency is a key parameter to consider it is not sufficient to rely solely on this as a means of ensuring that adverse social and environmental changes are minimised. For this reason there is need for some caution in applying the principle of water as an 'economic good' as an environmental management tool without also introducing safeguards to avoid certain damaging changes which are not directly related to water-use efficiency. The optimum solution to complex water allocation and management decisions is unlikely to be achieved through oversimplification of the problem.

To be aware of areas of special sensitivity

The key issues in relation to environmental change associated with irrigation and water resources development are likely to vary from locality to locality and project to project. It is necessary to be aware that certain regions or certain types of project are particularly sensitive. In relation to the physical environment the four factors which lead to particular environmental sensitivity in relation to irrigation are:

- areas of low or erratic rainfall

- areas where sediment loads in rivers are high whether due to high erodibility (e.g. the loess plateau of China) or to earthquake and volcano activity

- areas in which solute loads are high especially resulting from the re-use of drainage water

- areas with problematic soils.

In the biological and human spheres the factors leading to particular sensitivity are:

- areas which have hitherto been largely undeveloped

- areas of high population density

- projects which lead to rapid or large-scale social disruption or migration.

There are, moreover, different degrees to which environmental management may be expected to control or ameliorate adverse environmental effects. A desire to avoid certain changes would be virtually unreconcilable with the development of a region for irrigation: the preservation of the ecology of wild or undeveloped areas and the preservation of rural society with its particular socio/political and economic structures may both lie in this category.

Other changes, although having the potential for serious adverse effects, also have the potential, with appropriate resources and skill, to be managed in such a way that the net positive effects far outweigh the negative. Such changes include the control of pollution, the control of human disease, the control of weeds and pests, the achievement of economic and social well-being and the management of ecology within regions which have already been 'developed'.

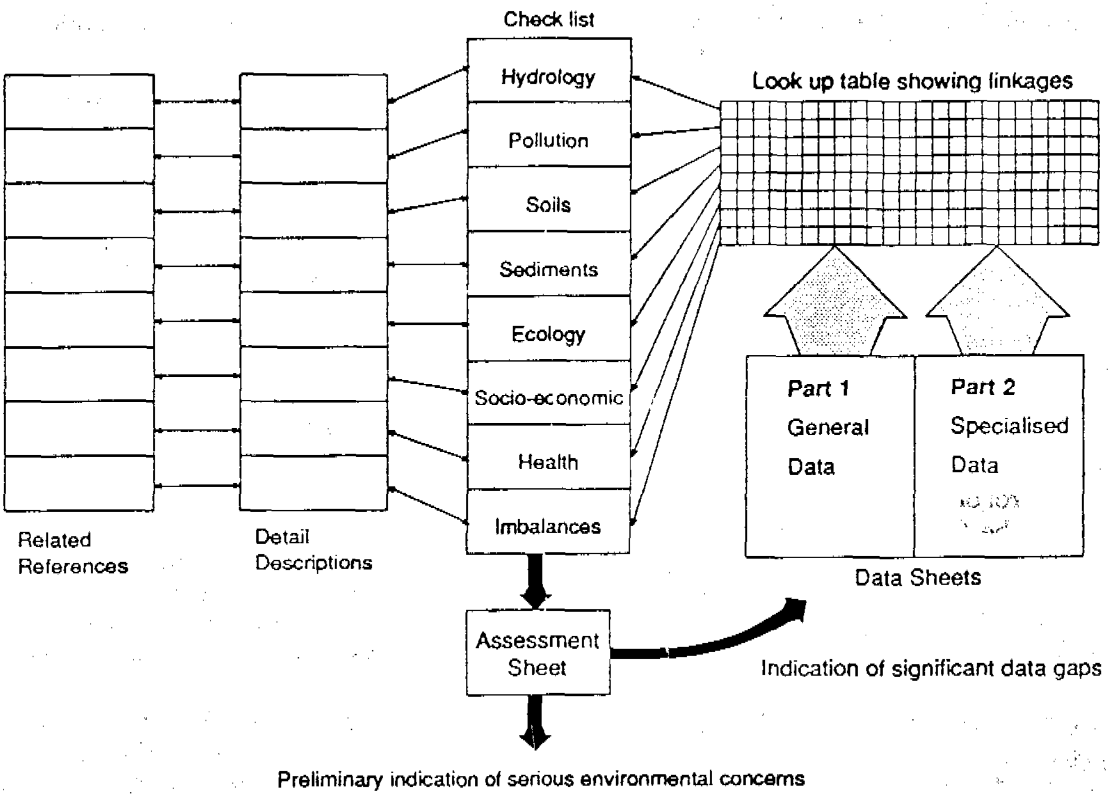
Two types of environmental change have potential for some amelioration through careful and well-resourced management but may nevertheless have cumulative impacts which will, in the long term, have important water resource management implications: the sedimentation of reservoirs and the salinisation of soils. Both must be studied carefully in relation to the sustainability of irrigation in certain regions and further research and strategic thinking are required to clarify the potential for managing these changes.

THE ROLE OF INTERDISCIPLINARY RESEARCH

Methods to identify key issues

In the above context of seeking to address complex environmental management decisions the ODU, through its collaboration with the ICID Working Group on Environmental Impacts, identified the need for a systematic procedure to assist engineers and others who are unfamiliar with many of the necessary environmental disciplines to highlight key issues in relation to the planning and management of irrigation, drainage and flood-control projects. The result of this initiative was the ICID Check-list which provides a comprehensive summary of the areas of environmental concern which should be considered in relation to these types of project (in this instance issues of 'sustainability' and 'impacts' were combined into a single category of effects to simplify usage). In its summary form (Figure 2) the Check-list appears to provide little practical guidance to the non-specialist user but the Working Group amplified the procedure by providing detailed descriptions, a targeted bibliography, data sheets for recording relevant information and results sheets for recording whether the user judges particular impacts to be important or whether he/she has insufficient data or knowledge to make a judgement. The relationship of the various components to each other is shown in Figure 3 and the first draft of the procedure is presented in Mock and Bolton (1991). The procedure has undergone field trials in a number of countries (including Pakistan and Sri Lanka) where the main benefits reported have been in relation to educating and involving the engineering profession in the environmental implications of their planning, design and management decisions.

FIGURE 3
Procedure for assessing key issues based on the ICID Check-list



Education and involvement of the non-specialist are the primary objectives of this work rather than to replace the need for specialists in the various environmental disciplines. This is well illustrated by one of the ODU's current research projects, in northern Nigeria, in which a questionnaire developed under the framework of the ICID Check-list is being used to collect information about the environmental status of some existing small irrigation schemes (see Bolton *et al.*, 1990 and 1991). In this, and many other similar situations, there are few resources available to undertake thorough environmental studies but the people with first-hand knowledge of a particular project (the project manager, the community leaders, the village health workers) are not pooling their knowledge, nor are they trained to assess the implications of their local knowledge in terms of environmental change. The questionnaire enables an initial assessment to be made of the most important health and environmental factors so that specialist help and advice can be targeted to best effect. In other words, non-specialists are able to use the procedure to undertake an initial scoping of the situation in order to optimise the use of scarce specialist skills. The preliminary work, in which a team of scientists collected field data to validate the results obtained from the questionnaire, suggests that this approach has merit both for identifying hitherto unrecognised problems and for creating awareness and understanding amongst the project officials.

Development and testing of methods for environmental management

With reference to Figure 1, I believe that the principal areas where new initiatives and research are required are in the areas in which there is an overlap between the three broad spheres of knowledge, physical science, biological science and human science. I have deliberately highlighted these three spheres because the disciplines within them have, to some extent, developed under different sets of principles concerning the way in which new knowledge is acquired, validated and presented. They also have different understandings about the ways in which systems behave and about the extent to which future change can be predicted. I have become particularly involved at the meeting-point of physical and biological sciences. It took me some time to understand that my fundamental belief in the deterministic nature of physical systems (excluding sub-atomic phenomena) and the over-riding desire to describe their behaviour with rules which enable quantitative generalisations and predictions to be made is not embedded so deeply within the fundamental tenets of biological scientists. Their outlook is more strongly descriptive and probabilistic: the desire to prove direct causality is less strongly present.

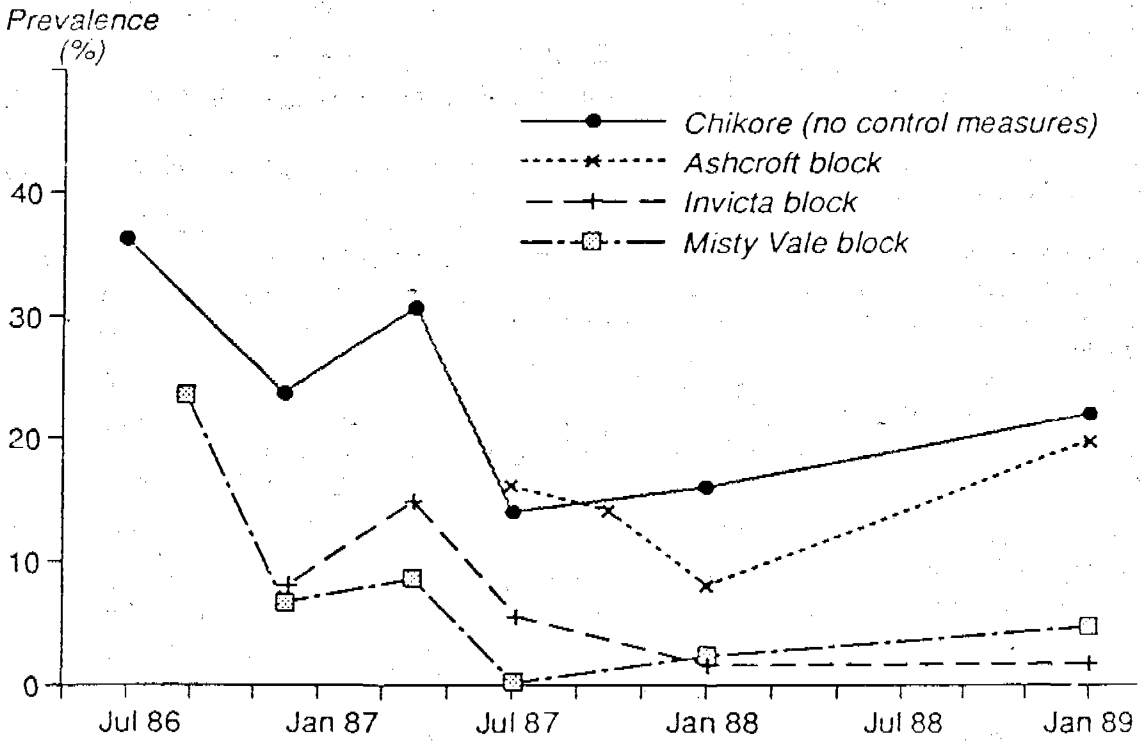
The different approaches are highlighted when joint research is attempted in the field of environmental management. Engineers and physical scientists are accused by biologists of being too ready to ascribe causality in situations where changes may simply be coincident and of being too ready to generalise without understanding that only slight changes from one situation to another may result in major differences in the response of biological communities. Biologists, on the other hand, are accused of being too tied to scientific procedures which are observational rather than experimental and, therefore, of being too cautious in designing studies which will demonstrate how changes in the management of a physical system may affect biological productivity.

The main focus of my own research in this area has been the developing and testing of measures for the control of water-related disease in irrigation systems. In particular, the ODU has recently completed the first phase of a seven-year study in Zimbabwe to develop techniques which engineers can adopt to help reduce the transmission of schistosomiasis (see Chimbari *et al.*, 1991 a and b). The study has attracted particular attention since few previous attempts have been made to pilot test methods for the environmental management of schistosomiasis within an operational irrigation project. Measures under investigation involve physical changes to the irrigation system to discourage the colonisation of water bodies by the aquatic snails, which are the intermediate hosts of the disease (canal lining, development of free-draining irrigation structures, careful scheduling of irrigation releases, attention to the design and operation of local storage ponds and adequate drainage provision), to discourage humans from contaminating water bodies (construction of household and in-field latrines) and to discourage humans from coming into contact with infected water (careful village location and provision of adequate, safe supplies of domestic water).

To a large degree, practices which are considered good engineering are also good for reducing schistosomiasis transmission. However, as the preliminary results indicate, see Figure 4, the effectiveness of these measures is variable and difficult to predict. In two of the irrigated areas, disease prevalence appears to have been held at a low level for three years whereas in a third, where similar measures had been introduced, the prevalence has risen to a level equivalent to that in an area without control measures. The research has increased our knowledge about the effectiveness of particular control measures but has also highlighted the difficulty of controlling this disease by environmental means: deviation from the recommended control strategy by only a small amount may result in transmission levels which are as high as if no measures were used.

Of more direct relevance to the subject of this paper are some of the lessons learned concerning the overall strategy for control and the methods by which research can be undertaken. In terms of strategy, the work has clearly demonstrated that to focus on planning and design alone is mistaken. Irrigation systems mature with time and biological communities change and adapt. More focus must be given to the dynamic aspects of control and, in particular, to the involvement of the local community so that they can be enabled to monitor the situation and know how to respond to changes which might occur. In this way research which was previously considered to be interdisciplinary only to the extent of involving the physical and biological sciences is now seen to include an important human element as well. With regard to research method, the work has demonstrated the importance of working within the constraints of a normal operational irrigation scheme rather than in a 'laboratory'. The Zimbabwe work has shown the importance of considering financial, social and administrative constraints in seeking to develop environmental management measures suitable for wider replication.

FIGURE 4
Prevalence of schistosomiasis (haematabium) in adults and pre-school children, Mushandike, Zimbabwe



CONCLUSIONS

The conclusions of this paper reflect the personal interests and experience of the author rather than presenting a comprehensive review of the subject. Particular emphasis has been laid on the need to clarify terminology. The suggestion made is that the 'environment' should include all physical, biological and human components (see Figure 1), that ideally 'sustainability' is the preferred term when discussing environmental changes which affect the project or region over which the interested person or institution has responsibility and that the term 'impacts' be used to refer to changes for which another individual or organisation has responsibility. This distinction clearly has little relevance unless responsibilities are first set and agreed. The special circumstances surrounding environmental change in developing countries are discussed and point to the conclusion that techniques of environmental management developed for temperate conditions are not adequate to address the situation in tropical developing countries: new techniques must be developed and field tested. Because of the diversity of factors that must be considered some attempt must be made to pinpoint key issues. The primary consideration in many cases is to improve water-use efficiency since not only does this reduce the likelihood of conflict in water-short situations but also water-use efficiency and 'wastage' relate directly to several important aspects of environmental change. The identification of key issues must be supported by an awareness of areas of particular environmental sensitivity.

Among the large number of possible research topics which relate to this subject, two have been discussed from the author's own experience: the development of procedures to enable engineers and other professional groups who do not have specialist environmental knowledge to recognise existing or potential environmental hazards in order that specialist assistance can be sought; and the development and field testing of environmental management techniques for the control of water-related parasitic diseases. In each case the work points to the need for a reassessment of the relationship between subject disciplines, for an awareness of the financial, social and administrative constraints within which environmental management techniques will be applied and for a pragmatic recognition that, faced with the complexity of environmental relationships and systems, a small step in the right direction, albeit taken cautiously, is better than no step at all.

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DISCUSSION

In discussion it was commented that the interacting role of the political economy should be highlighted further in Figure 1 and that an appropriate blend of politics-economic-biosphere is necessary. A note of caution about the success of irrigation in raising agricultural production was expressed since pest and disease incidence often increases at the same time; the extended cropping season enables pests and diseases to overcome natural limitations imposed by the absence of food or host plants. The question was raised as to whether sufficient account of these factors was being taken in the planning and management of irrigation schemes.

PAPER 13

Water management for aquaculture and fisheries; irrigation, irritation or integration?

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Summary: Aquaculture and fisheries represent a valuable component in food supply and have a useful role in many development initiatives. The sector is dependent for its potential on suitable water resource management, and there are important interactions to be considered within the wider context of planning, physical development and environmental management. This paper describes some relationships between aquaculture and fishery production, and the water resources which support them, and outlines practical implications for developers and managers.

INTRODUCTION

The supply of food and other products through aquaculture and fisheries constitutes one of the most direct and yet highly dependent goals in water resource management. From the local through to the global level, the continuity and interdependence of water resources, their subtle and intimate connections with harvested species, and the many levels of society and economy which depend on these, mean that almost any intervention must have consequences for human well-being. While aquatic ecosystems and the species they support may be tolerant of substantial external change, and may continue to be productive under even the most constrained of circumstances, we see increasing evidence of damage in the wake of the land-use and water resource effects of population growth, and economic and physical development. However, armed with the knowledge of the potential which could be realised, and given the opportunity to incorporate aquatic production goals into water resource management, there are clear prospects for improving the situation. This paper considers the relationships between aquaculture, fisheries and the water resources which support them, and outlines the practical implications for developers and managers.

FISHERIES AND AQUACULTURE: RESOURCES AND DEVELOPMENT

Table 1 summarises the recent status of aquaculture and fisheries production; this is based on aggregated national catch and production statistics and includes food and industrial processed fish (e.g. for fishmeal), crustacea, molluscs and seaweeds, but includes only variable amounts of artisanal fisheries and non-food production, and eg aquatic plants. Most prognoses of fishery supply suggest that capture fisheries are unlikely to grow by more than 1 or 2% per year and will ultimately be limited by physical and biological capacity, by deteriorating environments, and by increasing resource and energy costs of exploitation. Aquaculture by contrast has been widely promoted as compensating and ultimately supplementing traditional fisheries. Unlike fisheries, inputs, production processes and quality of output can be controlled to some extent, and ownership, care and some degree of environmental responsibility can be more readily established. By removing stocks from natural constraints of survival and productivity, and by husbandry and management, production need be limited only by the availability of inputs, land, water, seed, fertiliser and feeds. In 1988, aquaculture production accounted for some 14% by weight of total fisheries production, more than doubled over the last 15 years. By the year 2000, farmed aquatic production might account for some 20 million tonnes per year, some 16-18% by weight, and perhaps as much as 45% by value.

Regional production, and the relative importance of fish in national consumption, and in particular that of quality dietary components, is summarised in Table 2, which indicates that fish products represent a small but important role, and that LDC areas demonstrate a shortfall in supply, partly reflected in the smaller share in total fishery supply. Though not shown here,

TABLE 1
Fisheries and aquaculture production

Year	Total catch	Fisheries (10^6t)	Aquaculture (10^6 t)
1984	83.9	77.3	6.6
1988	98.8	87.9	10.9
1989	99.5	88.4	11.1
1990	95.6		

Source: FAO statistics; New, 1991

TABLE 2
Regional production and importance of fish in protein supply (1984-86)

Region	1984 (10^6 t)	1986 (10^6 t)	Total protein (g/caput/day)	Fish protein (%)
World	83.5	91.5	70.1	5.4
Developed countries	42.8	43.4	101.2	7.5
All LDC	40.7	48.1		
Sub-Saharan Africa	2.8	2.8	53.3	4.5
China	5.9	8.0	62.1	3.5
Asia/Far East	18.2	19.1	54.3	5.2
Latin America	10.4	14.0	68.5	3.4
Near East	1.8	2.0	80.0	1.6

Source: FAO statistics

and in spite of changes in territorial rights in marine fisheries, much of the recorded catch in LDC areas, particularly in Africa, the Pacific and Latin America, is also fished by international fleets, many of which are of developed country origin.

As Table 3 indicates, the bulk of fisheries production comes from marine sources, of which the majority originates from traditional 'open ocean' catches. Thus in Thailand over the 1974-80 period, about 6% of shrimp production was from aquaculture, 22% from small-scale (inshore) fishery and the remainder from larger-scale industrial fisheries, while in Indonesia in 1977 coastal (mangrove) dependent fisheries were about 3% of total marine capture (FAO, 1985). While the balance in this region has more recently changed towards coastal aquaculture, the relative dominance of open-water fishing still exists. As this resource is also ultimately dependent on water management decisions, it is more appropriate here to focus on those resources which are most directly involved in water management strategies; i.e. inland and coastal fisheries and aquaculture. The main focus here is therefore on the more explicitly managed water resources and the more directly controllable fishery outputs.

THE ROLE AND USE OF WATER

The availability and quality of water resources is clearly a key factor in determining where and how fisheries and aquaculture may be supported or developed. As a medium, water provides direct life support, nutrient exchange and food production, as well as providing environmental and behavioural context, and the conditions in which stocks can be controlled, protected or exploited. The relationships involved, although at times complex, depend particularly on the

TABLE 3
Fishery sector production 1989 by environment/habitat

Environment	Total catch (10^6 t) [% total]	Fisheries (10^6 t) [% total]	Aquaculture (10^6 t) [% total]
Inland	13.8 [13.9%]	7.4 [7.4%]	6.4 [6.4%]
Coastal/marine	85.7 [86.1%]	81.0 [81.4%]	4.7 [4.7%]
Total	99.5 [100.0%]	88.4 [88.8%]	11.1 [11.2%]

Source: FAO Fisheries Statistics, 1991, modified from New, 1991

habitat involved, the species and life-cycle characteristics, and the nature of the production system. Table 4 summarises some of the important points.

A fishery or aquaculture system may be vulnerable at any life-cycle stage and to any of these processes, and the absence of satisfactory conditions in only one respect may jeopardise the entire production potential. Nevertheless, many systems can be surprisingly robust, and may respond to external influence by, for example, changing the relative importance or distribution of species mix, rather than an absolute fall in output. However, much quality and value may be lost in the process when simple measures may have permitted or even expanded the original potential. In some cases aquaculture techniques can be used to circumvent or constraints in 'natural' systems, but the existence and mechanisms of these constraints must be recognised and defined before action can be considered.

Water resources and their potential

For the purpose of fisheries and aquaculture production, distinctions can be made between:

- inland water resources; streams, rivers, floodplains, lakes, reservoirs, ponds, groundwater, irrigation supplies
- coastal water resources; ponds, lagoons, estuaries, mangrove areas, inshore reef zones.

Unlike fisheries, production statistics for aquaculture versus resource volume (Table 5) demonstrate low relative utilization of marine resources. Although volume definitions such as these do not account for mean residence time, and e.g. nutrient cycling and accumulation, they serve to illustrate the relative 'loadings'. Surface waters are most intensively used, and of this much is abstracted from rivers or streams, though some is in conjunction with irrigation. A UK survey in 1982 showed the majority of aquaculture to be based on river water, although spring and well supplies were also used, particularly for hatching and growing juvenile fish (Solbe, 1982). In Scotland there has been an increased use of freshwater lochs (lakes) for salmonid cage culture. Cage culture of freshwater and marine fish has expanded widely in recent years; lakes and reservoirs, either for cage culture or 'culture-based fisheries' are increasingly involved (Beveridge, 1987). Groundwater is less important globally, though may be significant in e.g. catfish and trout farming in USA, carp hatcheries in Bangladesh, shrimp farms in Taiwan, trout, seabass and turbot aquaculture in Europe. In the Philippines, the majority of ponds use irrigation water (39%) some use pumped groundwater (32%) or surface runoff and springs (29%). By contrast, industrial or municipal wastewaters are rarely used. Although the intensive aquaculture of high-value species has more scope for using a wider range of water resources than low-input extensive or semi-intensive systems, the general focus on readily available resources increases potential for conflicts with other users.

TABLE 4
Water resources, habitats and life-cycle requirements

Life-cycle stage	Habitats/systems	Factors	Relevance
Maturation	Rivers, lakes reservoirs, lagoons, open sea, ponds, tanks, cages, enclosures, capture traps, nets	Feeding, competition, seasonal changes, temperature, water quality, depth, broodstock capture	Availability of broodstock for fisheries and aquaculture, maintenance of stocks
Migration (if involved)	Rivers, lagoons, open sea ladders, passes, traps, aquaculture stock/system manipulation	Access, protection, passage, water level, salinity, quality/stimuli, seasonality, sufficient numbers, capture/control for regulation	Potential of spawning stock to reach correct habitat to be well-conditioned in culture
Spawning	Streams, river/lake edges, floodplain, coastal fringe, open sea, ponds, tanks, system manipulation	Access, protection, substrate, water supply/quality, spawning stimuli, territory, currents	Ability of stock to spawn and eggs/larvae to be successfully protected/dispersed etc.
Larval/fry stage	Streams, river/lake edges, floodplain, coastal fringe, sea, ponds, tanks, cages, enclosures, nets	Access, protection, substrate, feeding, water supply/quality, temperate, currents, larval capture conditions	Ability of larvae to disperse, find habitat, feed, avoid predators, grow in natural or culture conditions
Migration (if involved)	Streams, rivers, lakes, coastal areas, open sea, stock/system transfer	Water supply/quality, currents, temperate, salinity, protection, passage, seasonality	Potential or young stock to move to main growing areas/suitable culture conditions
Growth phase	Streams, rivers, lakes, reservoirs, floodplain, coastal areas, open sea, aquaculture facilities	Access, protection, territory, feeding, water supply/quality, selection/grading, management control	Ability to find/use territory , feed, avoid predators, disease, grow in natural or culture conditions
Capture/ harvest	All habitats, river and lagoon traps, fishing nets, traps, lines, aquaculture harvest equipment	Access to harvest, aggregation of stock, control/drainage of water, avoidance of damage to non-targets	Efficient collection, capture selection, delivery of fishery and aquaculture product

TABLE 5
Aquaculture production/water resources

Environment	Volume (10^{12} m^3)	Aquaculture production, 1986 (mt)				Production/ volume ratio (mt/10^{12}m^3)
		Finfish	Molluscs	Crustacea	Seaweed	
Freshwater lakes	125	200 000				1600
Rivers, streams	1.25	4 500 000	10 000	120 000		3 700 000
Groundwater	8 250	100 000				12
Saline lakes/ inland seas	105	1 000				10
Seas and oceans	1 320 000	375 000	3 200 000	270 000	2 700 000	5

Source: Wilson, 1984, and estimates based on FAO data

Key characteristics of accessible resources with respect to fisheries and aquaculture are as follows:

Surface freshwaters: Surface freshwaters including streams, rivers and temporary bodies such as floodplains; can be particularly vulnerable to human influence, including physical obstruction, impoundment, containment, pollution; support wide range of species including anadromous/ catadromous migratory fish; often subject to complex seasonal/water level interactions, with dramatic short-term changes in productivity, as related to water quality, flow regimes, diversity of flowing water habitat. Conventional aquaculture potential primarily relates to pond, tank and raceway culture; also cages and enclosures in rivers, and hatchery/fingerling production for stocking temporary water bodies. Water quality is determined largely by topography and solubility of catchment, climate and the nature and extent of any pollution sources. Pollutant and natural solute concentrations tend to increase from source; pollution of remote catchments by acid rain and radiation products emphasises pervasive effects of human influence. Amplitudes of short- and long-term flow are important in suitability for aquaculture; e.g. development may be constrained by minimum flows, rather than mean flows.

Static freshwaters: Static freshwaters, such as ponds, lakes, reservoirs, normally have more stable physical and chemical characteristics. Related to flushing time, controlled fertilisation allows highly fertile pond ecosystems, successfully used in many tropical and subtropical regions. These systems are also of considerable interest for cage culture, aquaculture-based fisheries, and water supply or storage. There can however be problems from waste accumulation from intensive cage aquaculture (Beveridge, 1984; Phillips *et al.*,1985). Water bodies are characterised by factors such as overall shape, average and distributed depth, permanence of volume, their nutrient characteristics and trophic states, incident solar and wind energy, the degree and effects of mixing and turnover of water, seasonal effects, as well as their importance for other social or economic objectives. Overall they are complex systems, heavily biologically mediated in their potential. For fisheries-management based aquaculture, the priorities are to identify the biological capacity and its constraints and to identify the forms of aquaculture most suitable to assist in effective management and development. For more intensive aquaculture, the main priorities are to ensure adequate exchange of water and sufficient 'processing capacity' to handle the additional nutrient loads generated within specified criteria for lake condition. Additionally there should be sufficient space for physical and service facilities involved, and there should be sufficient 'activity capacity' to accept the needs of other users.

Groundwater supplies: Groundwater supplies (artesian or other wells, springs and groundwater-fed ponds) are of interest for aquaculture, particularly for hatcheries, and usually have more stable chemical characteristics than surface waters, although they may contain undesirable levels of dissolved salts and metal ions, low levels of dissolved oxygen and high levels of toxic gases (carbon dioxide, hydrogen sulphide). There is increasing concern about contamination of groundwater supplies by persistent pollutants which may also prove detrimental to aquaculture (there is also concern about aquaculture contributing to this; e.g. nitrogen from operations in Bavaria; Solbe, 1987; Taiwanese shrimp ponds).

Coastal water supplies: Coastal water supplies may be relatively stable, though estuarine coastal water, influenced by large and/or periodic freshwater effluxes is more variable, with a risk from pollution, salinity and temperature fluctuations. Additional problems of marine water include fouling organisms and blooms of toxic algae. Coastal areas may be critically important for intermediate life-cycle stages of marine species and often support extensive artisanal fisheries. Inland areas though accessible to brackish waters are increasingly reclaimed for agriculture and may be extensively damaged by pumping or retention of saline water for aquaculture. Aquaculture can be developed by placing the culture system directly into a suitably sheltered or protected area of the sea, e.g. cage culture, suspended mussel culture or sea-bed ranching of clams; by channelling into ponds, e.g. shrimp farming, or by pumping ashore for more intensive tank-based systems. This last is rarely economic because of the high capital cost of tank construction, and operating costs of pumping.

Industrial sources: Aquaculture has been successful in using water e.g. warm cooling water from nuclear power stations and municipal tap-water supplies. Heated effluents are frequently supersaturated with nitrogen and other gases and other industrial and municipal waters may be contaminated with various inorganic and organic compounds which may require pre-treatment or culture of appropriately tolerant organisms.

Wastewaters: Wastewaters hold considerable potential in the longer term, and approaches for wastewater use are being developed widely throughout the world, particularly in association with increased integration of municipal-level wastewater treatment and disposal. Possibilities include the direct use of fish culture in association with wastewater treatment, e.g. as a component in secondary or tertiary lagooning systems - with some limit to the extent of use, e.g. with specific processing or 'polishing' e.g. in clean reservoirs, or to use as feed or fishmeal resource, or to use e.g. for broodstock, where pathogen transfer to succeeding generations could be avoided. There is also more potential to use wastewaters in irrigation schemes with integration of fish culture in supply channels and/or intermediate storage ponds - subject to similar public health/ acceptability constraints. Wastewaters may be used to recharge reservoirs, e.g. for irrigation purposes, stock could be transferred to 'cleaning reservoirs' prior to harvest. Although technical means are available for carrying out these approaches, there remain problems of public perception and acceptability, even if wastewater is treated, let alone using it for direct production of food. However it can be noted that adventitious sewage enrichment already contributes to fish production in many water bodies.

Water quality criteria

A primary constraint for the use of water is its quality; equally the processes of aquatic production, particularly the more intensive forms, may bring about quality changes which may affect the system itself or its suitability for other uses. Although a water supply can be a source of toxins it is also important for receiving and dispersing excretory products and other waste materials which are harmful if accumulated. Water-borne organisms such as phytoplankton and bacteria also control quality in slow-flushing systems; water itself may detoxify wastes e.g. the pH of most freshwater and sea water allows excreted ammonia to be rapidly converted to non-toxic ammonium, whereas terrestrial animals use energy-intensive mechanisms to remove ammonia. Quality criteria are commonly divided between external (exogenous) and internal (endogenous) factors:

- *External:* inherent feature of water supply, usually from outside the site, independent of aquaculture or fishery activities. Cost-effective control is difficult but may be carried out by: choice of site, chemical treatment (e.g. liming, flocculation, oxidation, chlorination), physical treatment (e.g. screening, filtration, settling ponds for solids), re-using the water supply

- *Internal*: produced by stock itself, or by activities associated with fishing or culture (e.g. harvesting, feeding or disease treatment). Particularly in intensive farms with heavy feeding and high stock densities, where internal loading of waste food and excretion may be as important for stock health as external loading, it becomes crucial to match stocking and feeding with species tolerance to: ammonia, nitrite, suspended solids, biochemical oxygen demand, anaerobic conditions, treatment chemicals.

The effects of water quality depend on the species and life-cycle stage (e.g. larvae, fry, fingerling, grow-out etc.). As conditions deteriorate (one or more criteria reach limits), stocks become stressed. It is important to consider both lethal and sub-lethal effects, and factors such as handling, crowding and disease treatments. The extreme response to high levels of stress is mortality. Below this level, stress can:

- affect stock behaviour (e.g. predator avoidance, feeding behaviour)
- reduce growth/maximum size/food conversion efficiency
- impair reproduction (e.g. low egg fecundity, spawning success)
- reduce tolerance to disease
- reduce the ability to tolerate further stress.

The last two are crucial, because they imply that disease can follow any non-lethal but stressful pollution and that a combination of two or more factors, for example handling and high ammonia levels, can be more damaging than (a possibly more serious) exposure to one factor alone.

SPECIFIC WATER DEMAND

Water use and production systems

In fisheries, where production is more commonly considered to be incidental to the presence and quality of water, there is little concept of specific water demand, i.e. allocated to fishery production as opposed to other use. However, where, for example, river levels are managed for flood control or water supply, where lakes or reservoirs are controlled for power generation or irrigation, or where coastal areas may be affected by land reclamation or by salinity control, the overall relationships between volume, flow and fishery biomass may need to be entered into management decisions.

At a simple level, these may be defined by productivity relationships; e.g. production, per time period in kilograms per unit area, or per standardised unit of river length. While annual production is most common, a shorter time period may be more appropriate for seasonal or periodic water supplies. As noted earlier, availability, flow, level and/or quality characteristics may be particularly important at specific life-cycle stages, and production may be more closely related to these critical points than to longer-period features. Published productivity levels range with fertility and ecosystem characteristics but are typically of the order of 50-500 kg/ha/year in rivers, lakes and coastal water areas, and of the order of 1-5 kg/ha/year in open sea. However it is also important to consider the aggregation characteristics of fisheries, where apparent production may be greatly in excess of this in localised areas, due e.g. to seasonal feeding, migratory activity, and that of the wider water body correspondingly less.

In aquaculture, relationships with water demand are usually more clearly defined, as according to production system. This may be defined by the species (e.g. because of environmental or feeding requirements, or market value), which will in turn define the sites required. In other cases, a certain site may define which systems are feasible and may in turn suggest particular species. Alternatively a specific system will support certain species and require particular sites. Systems are usually defined according to two main criteria:

- *Type of system:* i.e. ponds, lagoons, tanks, raceways, cages, enclosures, rafts, ropes, trestles etc.

- *Intensity of production:* typically described as extensive, semi-intensive, intensive, etc.

Typical system characteristics are given in Table 6. These will clearly have a significant bearing on capital and operating requirements, and hence the project costs, and a variety of capital and operating input mixes can be defined.

TABLE 6
Aquaculture systems; outline design characteristics

System	Total water area (ha)	Mean residence time (days*)	Productivity (t/ha/year)	Capital cost/ tonne output	Water usage sensitivity
Ponds					
Extensive	10-1000	30-50	0.2-1	Very high	Low
Semi-intensive	1-50	10-50	0.5-2.5	High	Medium
Intensive	0.1-10	0.5-10	2-8	Medium-high	Medium-high
Lagoons					
Extensive	10-1000	10-200	0.1-0.5	Medium-high	Medium-high
Semi-intensive	0.1-10	10-50	0.5-2	Medium-high	Medium-high
Cages					
Semi-intensive	0.1-5	0.02-0.1	5-20	Very high	Medium-high
Intensive	0.02-1	0.02-0.05	50-400	Medium-high	Medium-high
Enclosures					
Extensive	0.05-1	0.05-10	0.5-2.5	High	Medium
Semi-intensive	0.01-0.2	0.05-5	1-5	Medium-high	Medium
Tanks/raceways					
Semi-intensive	0.05-2	0.05-5	10-50	Very high	High
Intensive	0.01-0.5	0.01-0.02	50-400	Medium-high	Very high
Shellfish systems					
Float/line	0.05-5	0.02-0.05	100-1000	Low-medium	Medium-high
Raft/rope	0.01-1	0.02-0.05	100-1000	Medium	Medium-high
Lantern	0.01-0.1	0.02-0.05	200-1000	Medium-high	medium-high
Trestle/bag	0.2-50	0.05-0.25	10-100	Medium	low-medium
Pole	5-100	0.25-1	5-50	Medium	low
Bed	5-200	0.25-1	5-20	Low	low

Water demand in aquaculture systems

Results from a range of production systems are shown in Table 7. Quantities per tonne of production vary widely, determined primarily through managed water exchange associated with intensity of production (i.e stocking density and use of feeds and fertilisers), but also through physical factors such as seepage and evaporation. It must of course be clarified that these figures do not (with the exception of static, high-evaporation systems) represent actual consumption, but account the quantities of water which have to be made available to bring about specified forms of production. The main implications are then the opportunity costs and the quality changes involved.

The table shows that the lowest water requirements are for the air-breathing walking catfish *Clarias batrachus* in Thailand. Above this, various tropical and subtropical pond systems have comparatively low unit water demand. The highest demands are for salmonids (and carp) in intensive flowthrough systems, with water being the only vehicle for supplying oxygen and removing metabolites. In ponds, seepage typically ranges from 2-25 mm/day, depending on soil

TABLE 7
Water requirements per tonne of aquaculture production

Species	System	Production /year (t/ha)	Water requirements (m^3/t)	Source
Clarias batrachus	Intensive static pond system (Thailand)	110-200	50-200	Muir (1981)
Tilapia (*Oleochromis niloticus*)	Sewage fed, minimal water exchange (Thailand)	6.8	1 500-2 000	Edwards *et al.* (1987)
Common carp/tilapia	Intensive aerated pond (Israel)	20.0	2 250	Sarig (1988)
Tilapia (*O. niloticus*)	Static rainfed extensive ponds	0.05-0.3	3 000-5 000	Muir and Beveridge (1987)
Common carp/ tilapia/mullet/ silver carp	Semi-intensive pond (Israel)	9.0	5 000	Sarig (1988)
Channel catfish (*Ictalurus punctatus*)	Intensive pond culture (USA)	3.0	6 470	Boyd (1982)
Common carp/ tilapia/mullet/ silver carp	Conventional pond culture (Israel)	3.0	12 000	Sarig (1988)
Tilapia (*O. niloticus*)	Intensive, mechanically stirred ponds (Taiwan)	17.4	21 000	Hepher (1985)
Channel catfish	Intensive raceway culture (USA)	300-800*	14 500-29 000	
Penaeid shrimp	Semi-intensive pond culture (Taiwan)	4.2-11	11 000-21 430	
Penaeid shrimp	Intensive pond culture (Taiwan)	12.6-27.4	29 000-43 000	
Penaeid shrimp	Intensive raceway culture (Mexico)	11.8	55 125	
Rainbow trout (*O. mykiss*)	Intensive raceways (USA)	150	210 000	
Salmonids	Intensive pond and tank culture (UK)	200-600*	252 000	Solbe (1982)
Common carp	Intensive raceways (Japan)	1443	740 000	Kawamoto (1957) in Hepher (1985)
Rainbow trout/ common carp	Various European farms (European survey, 1982)	200-600*	15 768-5 544 029	Alabaster (1982)
Salmonids (Scotland)	Cage culture	40-200	2 260 000	Phillips *et al.* (1988)

Source: Adapted from Phillips, *et al.*, 1988

* Estimates by author from industry standard production rates

type, pond surface area and wall construction. Losses through evaporation may reach 25 mm/day, though in the subtropics are more typically around 5 mm/day. With total losses of 10-20 mm/day, each hectare of pond will 'consume' 100-200 m^3 water per day. In Israel, total requirements for ponds are estimated by Hepher and Pruginin (1981) to vary between 35 and 60 000 m^3/ha/year to maintain an average depth of 1.5 m throughout the 240-day growing season.

Aquaculture has a comparatively high water demand (Table 8), may in relative terms add only moderate value from nominal use of water resources, and might therefore have a low priority when competing with industrial or agricultural users. However value versus water-quality change may be higher than for some competing users - see Table 9 (Muir and Beveridge, 1987).

TABLE 8
Typical water requirements of industry and agriculture compared with selected aquaculture systems

Product	Water use (m^3/mt)	Nominal value ($)	Water value ($/$m^3$ used)
Alcohol	125-170/m^3	2 000/m^3	12-16
Cotton	90-450	1 000/mt	2.2-11
Paper	9-450	300/mt	0.7-33
Steel	8-250	200/mt	0.8-25
Beef	42	2 000/mt	48
Pork	54	2 000/mt	37
Petroleum	21.6-810/m	500/m^3	0.6-23
Aquaculture shrimp ponds	11 000-55 000	6 000-12 000/mt	0.1-1.1
Salmonids	250 000	3 000-6 000/mt	0.012-0.024
Channel catfish ponds	6 470	2 500/mt	0.40
Clarias ponds	50-200	1 000/mt	5-20

Source: Modified from Schwab *et al.*, 1971 and Muir and Beveridge, 1987
Note: Figures for water requirement of pork and beef production refer to the total water requirement (i.e., feed plus drinking water)

TABLE 9
Production loading from aquaculture and other industrial and agricultural sources

	Production loading	
Product	kg BOD/mt	kg BOD/$ value
Textiles	120-180	0.12-0.18
Tannery	60-240	0.06-0.24
Brewery	18-24	0.02
Slaughter	8-24	0.002-0.006
Pulp	15-21	0.15-0.21
Aquaculture	200-1000	
Shrimp		0.02-0.06
Salmonids		0.05-0.60
Clarias		0.2-1.0

Source: Muir and Beveridge, 1987

Water quality changes

As fisheries are by definition associated with the natural productivity of water bodies, there are no specific water quality changes involved in its output, though there may be localised effects of fishing activity, such as sediment disturbance, and the more serious matters of poisoning or the use of explosives. There may also be water quality implications of measures associated with attempts to conserve or enhance fisheries, such as reservoir or river-flow manipulations. By contrast, aquaculture is often associated with water quality changes, which tend to increase with intensification. These have been sufficiently well studied to allow prediction of the nature and scale of potential impacts in most situations (e.g. Hakanson *et al.*, 1988). Impacts on the quality of receiving waters and on the associated sediments are of most concern, particularly in relation to the mass input of nutrients. There is also a variety of other effects, such as chemical treatments and genetic pollution, as discussed below.

Nutrients: Aquaculture effluents comprise waste products (urine and faeces) and uneaten feed, containing nitrogen and phosphorus in both soluble and insoluble forms. If in sufficient quantities relative to the volume of the receiving waters, this may lead to hypernutrification and stimulate undesired growth of phytoplankton, seaweeds and aquatic plants. However, due e.g. to bioavailability and potential limiting status of these nutrients, effects vary widely with the characteristics of the ecosystem.

Sedimentation: The solid fraction of effluents may deposit as sediment in close vicinity of the farm site. This may result in physical changes in nearby sediment, and in some cases, highly localised changes in the community of sediment-dwelling animals and plants. The chemical composition of sediments will also change, becoming enriched with organic material and nutrients (Kupka-Hansen *et al.*, 1991). Elsewhere, aquaculture installations will themselves act as controllers of exogenous sediment; e.g. trapping sediment in coastal supply sluices or in valley-floor ponds, and in return discharging some or all of these during periods of flushing or drainage.

Salinity changes: Where saline water is being pumped from coastal wells, problems may arise through salinity intrusion in the aquifer, affecting the aquaculture operation itself, and contaminating the aquifer for other users. The surface discharge of saline wastes from these and from coastal pumped farms may also have a substantial and longer-term effect on soil salinisation, and its potential for e.g. conventional crop production.

Chemical treatments: The use of disease chemicals, including compounds ranging from antibiotics such as oxytetracycline to parasite treatments such as malachite green and organophosphate pesticides (reviewed in NCC, 1989 and 1990), is widespread, particularly in intensive farming operations, and requires careful, compound-specific regulation and monitoring.

Escapes of stock: Fish cages may become damaged (e.g. by storms) and ponds or tanks may flood, resulting in the release of large numbers of stock. Smaller numbers may also be periodically lost to the local environment. If the species is indigenous the impact may be minimal, though if the scale of release is large relative to the size of the local population, 'genetic pollution', or dilution of the local gene pool may occur. If the species is imported, it may establish within the local environment and possibly spread to other areas with unforeseen consequences for the native aquatic communities.

ENGINEERING AND OTHER IMPLICATIONS

The previous sections have identified the main water management issues involving fisheries and aquaculture production and have commented on a range of constraints and effects. The relationships between the fisheries sector and other development activities, particularly those involving engineering and other forms of physical change, are further described in Table 10.

TABLE 10

Engineering, land use and fisheries; basic water management inter-relationships

Area of activity	Factors	Implications/constraints
Engineering development		
General construction	Soil disturbance, silt cement washings, diesel	Short-term toxicity effects on fish populations, silt covering spawning gravels, disturbance to flows, feeding
Quarrying, gravel extraction	Silt, removal of material from stream beds	Abrasive solids, removal of spawning grounds, destabilising stream beds, reducing feeding: possible use of redundant quarries for stocking, cage culture
River or stream modification	Flow changes, canalisation, marsh drainage	Disturbance to spawning, feeding, early life-cycle habitat reduction in floodplain fisheries; better control for aquaculture supplies
Damming and diversion	Flow reduction, changes in sediment transport, barriers to movement	Changes in habitat, impediment to migratory stocks changes in species mix, downstream concentration of pollutants; possible diversion through ponds
Reservoir development	Flooding, water level changes between siltation	Disturbances to habitat, access and feed supply in and downstream; chemical concentration opportunities for cage culture, controlled stocking
Coastal construction, flood protection,land reclamation	Reduced water exchange salinity, sediment change, reduced intertidal area, changed coastal currents	Reduced area for key life-cycle stages, reduced feed supply, greater access to capture, reduced flushing, seasonal change in habitat
Agricultural and other land-use practices		
Clearing of land	Physical and chemical destabilisation	Poorer environmental and feeding conditions, reduced seasonal stability, social/behavioural disruptions
Intensification of farming practice	Increased fertilisation, pesticide application, possible soil depletion	Changed environmental and feeding conditions, changed seasonal characteristics, possible toxic/accumulative effects, social/behavioural disruptions
Forestry plantation	Changes in interception, chemical, heat balances, soil destabilisation	Poorer chemical stability, possible toxic effects, changes in sediments, feed types/availability
Watershed management	Better soil management, terracing/erosion control, better nutrient control	More stable stream environments, less potential silt damage, possibly lower short-term feed opportunity, better longer-term stability, can fit in aquaculture
Aquaculture development		
Creation of inland ponds	Hold up water within watersheds, nutrient sink and processing, trap silts change local ecosystems	Possible reservoir of fertility, provide more stable water flow, seasonal availability, additional local food supply; may divert water from fishery needs, possibly increase waterborne disease risks

Table 10 contd.

Creation of coastal pond systems	Remove cover, possible exposure of acid soils, change salinity and silts, make protective walls	Protect inshore areas, improve potential for reclamation, disturb mangrove habitat, make local soils unproductive, contaminate land and water with wastes, pesticides
Development of shellfish or seaweed culture	Physical obstruction, nutrient depletion, sediment trapping	Impede access, use; build up sediments locally, change coastal habitats, local ecosystems; limit productivity, may increase coastal diversity/protection
Cage/enclosure culture in reservoirs, rivers, lagoons	Physical obstruction, nutrient enrichment	Impede access, use; build up sediments locally, change habitats, local ecosystems; possible negative feedback

Social, legal and other issues

The use of water for aquaculture or fisheries is often regulated either specifically, or as part of the right for fishing or agricultural purposes (van Houtte *et al.*, 1989). Until recently there have been few constraints in practice. However, where water is scarce conflicts can arise, and thus in Israel, where water is now priced, it has been found to be more profitable to use water for crop irrigation than aquaculture. Fish ponds have been rebuilt to form irrigation or dual-purpose fish culture/irrigation reservoirs and fish culture has been restricted to only part of the year (Hepher, 1985; Sarig, 1989). In many areas in the developed world, aquaculture, especially if involving river abstraction for pond farming, or the use of lake and coastal areas for cage sites, is being constrained by real or perceived effects on other users. In many traditional societies, water rights are carefully and often sparingly controlled, and access to these for non-traditional activities may be very difficult.

In Cyprus, problems of water allocation for aquaculture have recently emerged (Muir and Baird, 1992). Its dry Eastern Mediterranean climate means that water is crucial to the society and economy, and many traditional rights attach to water use and management. So strong are these, and the politically important rural societies' attitudes to water, that they distort rational allocation of what is in every respect a scarce resource. In spite of a recognised need to conserve, policies do little to constrain use; charges, particularly for irrigation and other agricultural purposes are substantially below costs of supply. Fisheries and aquaculture have little or no traditional status and are therefore almost completely excluded from resource allocation. Groundwater resources are heavily used and localised declines in water-tables are common. Although major groundwater development has taken place, with substantial investment in conveyor and recharge projects, much of this has been immediately absorbed into intensive agricultural production and domestic or tourist water supply. Problems of salinisation of coastal zones have been reduced by the various recharge schemes but supply is precariously balanced with little for aquaculture unless integrated, e.g. with irrigation. Reservoir storage capacity has reached 297 million m^3 out of a total 450 million m^3 net surface runoff. For irrigation supply reservoirs, cage-based trout farms have been established and there is a programme of stocking and restocking, mainly for sport fishing. However, capacity is now heavily absorbed, as around 90% of reservoir volume is stocked, 25-30% is used for aquaculture and reservoirs were until recently drawn down to extreme low levels. More reservoirs may be converted to potable supply and fish farming may not be able to continue. Although coastal seawater aquaculture has developed, waste nutrients were being blamed for a troublesome growth of filamentous algae which caused serious disturbance to coastal areas and major concern for tourist interests. Though the problem was more likely a response to the far greater enrichment from intensive agriculture and domestic and tourist wastes (Baird and Muir, unpublished), such was the public concern, that aquaculture was placed under an effective moratorium.

The changing nature of aquaculture may also affect its impacts and acceptability. Until the late 1960s, Taiwan's aquaculture was based heavily on traditional Chinese integrated polyculture in fresh and brackish water. Due to industrial development, consumer buying power increased, moving demand from traditional low-cost products such as carp and milkfish to more intensively produced quality species like eel, grouper, and shrimp. Aquaculture was based on small family units of 1-3 ha; shortage and very high cost of land have meant that most systems have intensified, requiring constant management - uneconomic if families were not involved and labour had to be hired. In 1981 aquaculture took 11% of Taiwan's total water consumption, some 21 million m^3, mostly from shallow (about 8 m deep) boreholes, giving unpolluted and temperature stable water (25-26°C). In the last five years uncontrolled development for intensive shrimp farming stretched this resource, and overpumping has led to land subsidence, sometimes exceeding 2 m. Pollution problems and disease have also affected the industry and contributed to the collapse of production from 80 000 t in 1987 to 20 000 t in 1988. Increased competition from mainland China and throughout the rest of Asia has created further uncertainty. However, recent government control over licensing water use and effluent discharge, combined with better management practices, may help the industry as it evolves in the future. Meanwhile, this experience provides a good cautionary example for the planning and development of aquaculture (Phillips *et al.*, 1988).

The role of local and international development and investment projects might also be noted. Though many agencies understand fisheries and aquaculture to make a contribution to basic development aims, investment has often tended to support projects aimed at export production and foreign currency earnings - valid perhaps for structural readjustment - or has been imprecisely targeted to potential beneficiaries. Heavy commercial investment (local and international) has also tended to focus on the more obviously profitable areas of aquaculture, often at considerable cost to local resources and environments. Thus by the late 1980s, penaeid shrimp farming was Ecuador's most important export after oil and bananas, and in Bangladesh shrimp exports became second only to jute. In both areas, however, environmental and social issues cause increasing concern. Rather than banishing such development, or denying its positive impacts, there is perhaps a more pressing need to improve efficiency, control impact and reduce conflict.

Improving efficiency

There is an increasing trend towards intensifying fishery and aquaculture production. This has resulted in different approaches - and with most species (e.g. salmonids, channel catfish and shrimps) resulting in increased water use. Intensive, high flow-rate systems are rare in developing countries; most are in urban areas or where water is scarce; high water use is common only where water is plentiful and/or there are no laws or costs to restrict use. There would appear to be ample scope for improving efficiency of water use; an EIFAC survey of European freshwater farms (Alabaster, 1982), showed water consumption per tonne to vary more than 100-fold. Where conservation of water is necessary or desirable and cost penalties are enforced, water use can usually be reduced. Thus in Israel intensified culture of common carp and tilapia has accompanied a decrease in water use (Hepher, 1985; Sarig, 1988), primarily because of the high cost of water, and the priority given to water conservation. Species tolerating poor water quality (e.g. catfish) can also be produced with little increased water use.

Where possible, there may be distinct advantages for fisheries and aquaculture to be integrated with other industries or with agriculture. There may also be benefits where for example aquaculture can add value to a water resource, e.g. with fish production in sewage fed ponds, to improve water quality and generate income from a waste material (Edwards *et al.*, 1987; Little and Muir, 1987), or where improved fishery yields can add discernably to the benefit streams of a capital project. There may be opportunities for environmental enhancement or rehabilitation; in Scandinavia researchers are attempting to improve water quality in acidified freshwater lakes through selective 'pollution' by cage culture (Solbe, 1987).

For fisheries the main inputs towards improving efficiency lie in improving the utilisation of water bodies, controlling stock yields and economic value, possibly using hatchery stock, nursery techniques or other aquaculture-based methods to supply or supplement production. Such approaches would be based on the use of traditional fisheries management techniques, together with assessments of local social and economic characteristics to identify target groups, use rights and custom, and to define cost-effective and sustainable management methods. For aquaculture, the main aims would involve more flexible use of available permanent or temporary water resources, improved nutrient transfer from inputs to product, and practices which minimised external impact. This can be achieved in a range of ways; by modifying construction and design, amending operation and management, or by applying technical treatment.

Ideally, aquaculture operations should be conceived from the outset to minimise impact, though for a variety of reasons - lack of incentive, lack of awareness of problems and/or site or operational characteristics - many problems are dealt with retrospectively, through modification. Design and construction factors include: at the general level - designing the system to maximise payoff between productivity and environmental effect, i.e. to get the best, most efficient performance with as little as possible environmental 'cost'; at the specific level - careful site selection to ensure minimum impact on sensitive areas, whether visually, physically in terms of cover/erosion, or biologically in terms of ecosystems and/or individual species; where necessary, providing adequate mixing, dilution and dispersal; if needed, providing waste and impact management measures; designing to minimise releases, contact with external water supplies, transfer to other stock, disease contamination; limiting construction disturbance, keeping top-cover, avoiding discharge of materials into water courses.

In operation and management, control can be exerted at each step in the production cycle; e.g. with better formulated, more digestible and water-stable feeds and better feeding methods. There is considerable economic pressure to minimise feed losses - this was in part responsible for a more than 50% drop in effluent solids loadings per unit production, observed from UK land-based farms between 1980 and 1987 (Solbe, 1987). Other factors include: care over incoming stock and genetic consequences; stock density/system management control; feed control to optimise efficiency rather than growth; use of fallow sites; controlling the use of chemicals and the transfer of resistance, predator control; changing ways of disposal of mortalities; restricting numbers of different stocks and, hence, the possibility of disease transfer.

Water treatment may be used to improve stocking densities and reduce requirements. This already exists in extensive and semi-intensive ponds which are managed to promote phytoplankton growth as fish feed organisms or as a carbon source at the base of the food chain. Phytoplankton have the added benefit of producing oxygen by photosynthesis and assimilating waste metabolites. However, as stocking densities increase, more precise water quality control is needed to ensure adequate supplies of dissolved oxygen and efficient dilution and assimilation of metabolites and aerobic metabolism of organic wastes (Hepher, 1985). The tendency towards increasing water flows and decreasing water retention time in more intensive systems results in a loss of many of the internal water quality control systems and, inevitably, leads to even greater water demand. Flow regimes and production plans can be improved by design to maximise stocking per unit flow. Systems can also be intensified by varying degrees of water treatment, from simple aeration through to recycling using biological filtration, solids removal and oxygenation. As well as improving water economy, such systems can provide controlled environments, e.g. for temperature and/or salinity. They involve additional costs, though this may be justified by improved performance or the production of valuable species or stocks.

Water-use efficiency of existing systems can be improved with a number of means, including reducing seepage losses and intensifying use and re-use of water. Water loss from ponds can be reduced by better siting and management, and further minimised by increasing depth. Thus Sarig (1988) reports water losses from ponds to be 6-10 times higher (35 000-60 000 m^3/ha/year) than those from deeper dual-purpose reservoirs (~6000 m^3/ha/year). Seepage should also be reduced to control adverse production effects of high water exchange on alkalinity. Concrete-lined ponds as developed in Taiwan and Israel (Hepher, 1985) can help in intensifying water use, though waste output may be greater as there is much less opportunity for biotransformation. In comparison with more intensive flow-through systems, simple pond farming could also be proposed as being more water efficient, although large land resources may be required because of relatively low areal production. There may also be significant management problems with large volumes of water and low densities of stock. These may be partly overcome by culturing fish in cages in large ponds, as is now developing in several regions (e.g.

Hungary and Israel). Water can also be conserved by culturing fish species with improved tolerance to low dissolved oxygen and high levels of waste metabolites (e.g. tilapias).

Routine water conservation can also be implemented. Deepening ponds to increase storage has been recommended to conserve seasonal water resources (Hepher and Pruginin, 1981). Loss of water during harvest can be reduced by avoiding draining, although this may cause longer-term deterioration of water quality. Integrating agricultural water with aquaculture can benefit both (Little and Muir, 1987). In Israel, integration has been forced on fish producers because of the high value of irrigation water, and more than 20% of fish ponds have been turned over to integrated fish/irrigation schemes (Sarig, 1988). This has involved a shift to more intensively managed ponds or to cage and pen culture in larger irrigation reservoirs. There is also scope for increasing the fertility of irrigation water, to improve yields or maintain existing yields with lower levels of fertilisation. Fish-pond water has been used as a fertiliser for maize (Edwards, 1980) and for rice and vegetables in the Philippines, and pond sediments and water have been widely used as fertiliser for many years in China. In irrigated and rainfed rice fields in tropical regions, fish culture also offers potential for increasing output value. Water costs for fish culture are very low as the infrastructure and supply is already available, and management of soil and water is already present. Economic benefits through production of fish and increased rice yields can be significant. Fish culture can also improve the general availability of water resources. Stocking of irrigation canals with macrophyte feeders such as grass carp *(Ctenopharyngodon idella)*, java carp *(Puntius gonionotus)* and *Tilapia zilli* has also been used in several regions for removing machrophytes and improving water flow to traditional agricultural crops (Little and Muir, 1987).

Cage and pen culture do not require water abstraction and so offer good scope to improve water resource use. Cages have been used successfully in irrigation reservoirs (Beveridge and Phillips, 1988) and in a wide range of lakes, reservoirs and running waters (Beveridge, 1987). Problems associated with environmental impact are a continuing concern, although greater understanding of the interactions between cage culture, open stocking levels, environment and water quality should assist optimal use. Aquaculture can also be integrated with drinking-water supply; cages of filter feeding bighead carp have been used to remove phytoplankton from potable water reservoirs in Singapore (Beveridge, 1984). Integration of open water stocking or extensive cage culture with intensive aquaculture also offers scope to minimise or control eutrophication.

In coastal areas, saline water extraction and discharge can have considerable negative impact, and improved water use can be an important objective. The effects of saline intrusion or deposition can be reduced by positioning wells and screens carefully and limiting multiple well development, and by controlling extent, locations and/or timing of deposition. In freshwater zones it may be appropriate to recharge water from the aquaculture operation or other sources, using e.g. percolation pits or trenches. As well as recharging the groundwater resource, this can be useful for cleaning and decontaminating mildly affected supplies. Particular care has to be taken to avoid excessive nutrient loading and clogging of substrate pores, and to avoid direct contamination and immediate deoxygenation problems; it is useful to keep recharge areas well apart.

GOALS FOR WATER MANAGEMENT

Prospects for development

What are the prospects and constraints for maintaining and developing the fishery sector? Fisheries and aquaculture development of even the simplest form needs resources, management and reasonable social and economic stability. Areas where malnutrition is related to drought and crop failure are unlikely to have resources for aquaculture but may be able to support very important seasonal fisheries. In Africa's case, problems of production are partly bound up with internal political, social and economic changes, and with the external pressures of changing trade conditions. Asia by contrast, has a long history and association with fishery and aquaculture, and vigorous economic growth in relative political stability. In many areas, the two activities might be complementary; traditional dependence on capture allows consumption at significantly lower prices than are common for aquaculture, while the latter supplies more developed urban and export markets.

Where aquaculture has traditionally produced lower-cost supplies - e.g. the inland water carp culture of China, SE Asia and India, and the brackishwater milkfish production in Indonesia and the Philippines, products are either increasing in price beyond the means of the poorer rural communities, or are being supplanted by other higher-value cash crops. Within a given range of aquatic resource potential, lower-value products such as seaweeds, molluscs and local food fish may lose out to crops for export or for the more prosperous sectors of the society. While lower-value production from simple traditional methods continues to be significant in volume terms, its importance may become eclipsed. This section considers some of the implications for water demand.

The potential for water demand

The needs for water in the fishery and aquaculture sector have already been commented upon. As an illustration of the longer-term implications and based on aquaculture production only, Table 11 summarises the water involved in meeting expected production levels for the year 2000.

This usage would obviously be subject to the provisos already discussed but the table clearly indicates the scale of requirement, and the implications for water resource needs, and for the improved management of those resources involved. Additional allocation for aquaculture implies an equivalent change in availability or quality for other uses, whether for fisheries and environmental management, for agriculture, industry or potable supply. As suggested above, most of this would occur in the area of semi-intensive aquaculture, in freshwater, and would involve the management of surface-water supplies.

Themes for development

It is obvious that aquaculture and fisheries require to be seen within the wider views of e.g. aquatic resource use, land-use development, rural, regional, general economic development. Though it has frequently been claimed that aquaculture is very 'complementary', profitably using resources which are otherwise unused, all forms of aquaculture require the organisation and mobilisation of resources, whose use represents a removal from use elsewhere - whether productive, recreational, aesthetic. Capture fisheries, based on natural aquatic habitats and their productivity, are also traditionally considered non-demanding of resources and may even respond positively to additional 'waste' inputs. However, the opportunity costs of maintaining or re-establishing fishery production, and the importance of the communities this serves, might increasingly be brought into benefit assessment. Both in generalised planning and in specific design, it is important to be aware of these resource implications, and to consider the capacity of various locations and systems to supply resources. Increasingly, questions of aquaculture and fisheries in development will feature in the wider technical context, involving the understanding, management and rehabilitation in terms of individual ecosystems or ecotopes such as lake and river systems, lagoons, mangroves and coastal reef, in terms of understanding the characteristics and potential of ranges of production systems, and in terms of better characterisation of water resources, including domestic, agricultural and industrial 'waste' water. These components would then form part of a set of larger, higher-order multiple-linked systems and management approaches, such as:

- *Watershed management* - particularly for inland fisheries - involving issues such as water retention, local albedo effects and soil stabilisation; sediment collection, maintenance of nutrients and productivity; groundwater use, re-use and quality management; multiple use of reservoirs, lakes, and the development of multi-use ecological and economic models; incorporation in larger-scale projects for flood control, irrigation, water supply and wastewater treatment.

- *Coastal area management* - for brackish-water and marine aquaculture, coastal and lagoon fisheries - involving issues such as water exchange, physical development, sedimentation and salinisation, groundwater use, nutrient and chemical management.

TABLE 11
Projected water use by major species/production system

Environment/ system	Species involved [estimated % of total]	Production (10^3t) [% total]	Typical average water use (m^3/t)	Total water use $(10^6m^3/yr)$ [% total]
Inland/freshwater				
Extensive	Carps[1] [40], Tilapia[2] [30]	1700 [27.4]	10 000	17 000 [9.2]
Semi-intensive	Carps [55], tilapia [55], trout [10], catfish [25], prawns[3] [95], eels [5]	2540 [40.9]	5 000	12 700 [6.9]
Intensive	Carps [5], tilapia [5], trout [35], catfish [65], prawns [5], eels [50]	470 [7.6]	20 000	9 400 [5.1]
Super-intensive	Trout [50], catfish [10], eels [40]	180 [2.8]	200 000	36 000 [19.4]
TOTAL		4890 [78.7]		75 500 [40.7]
Coastal				
Extensive	Milkfish [70], shrimp [65], eels [5]	590 [9.5]	30 000	17 700 [9.5]
Semi-intensive	Milkfish [30], shrimp [30]	260 [4.2]	15 000	3 900 [2.1]
Intensive	Shrimp [5]	30 [0.5]	10 000	300 [0.2]
TOTAL		880 [14.2]		21 900 [11.8]
Marine				
Super-intensive	Trout[4] [5], salmon[4,5] [100], yellowtail, etc [100]	440 [7.1]	200 000	88 000 [47.5]
TOTAL		***6210 [100.0]***		***185 400 [100.0]***

Notes

[1] Includes common, grass, silver and bighead carp

[2] Tilapia also grown in coastal/marine areas but assumed negligible here

[3] Includes Macrobrachium and red swamp crawfish

[4] Onshore (i.e. coastal) production of trout and salmon occurs but assumed negligible

[5] Salmon also grown in freshwater but insignificant

There is considerable scope for greater integration between fisheries, aquaculture and water-resource management. Where social and other conditions permit the management and regulation of fisheries, or where existing natural resources are threatened by other activities, aquaculture techniques - broodstock selection, hatchery production - may become more important in supporting or enhancing fisheries. 'Biomanipulation', using aquaculture-based knowledge or techniques to enhance productivity of natural water bodies may widen opportunities for lower-cost food production. These techniques, rather than competing with other forms of aquatic production, should provide better means for managing aquatic resources, whether in terms of understanding natural populations of phytoplankton or fishery stocks, supplementing production with habitat structures and controlled releases of nursery stock, or manipulating environments for restoration or enhancement. This understanding should be broad and open-minded, and would comprise many different aspects of traditional planning and engineering, together with sizeable elements of biology, sociology and economics. We might aim for a similar understanding to that of agricultural systems, of the means to define the possibilities, what resources they require, and how systems can be successfully set up to meet our objectives. In spite of a difference of several thousand years' experience, there is no reason not to attempt similar approaches in aquatic resource use, and to develop the kind of practical framework in which we can research and develop, plan and manage.

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DISCUSSION

In the discussion the need to understand the political economy of fisheries and aquaculture was emphasised. In Bangladesh, for example, freshwater fisheries have been neglected and are subject to interference from other water interventions especially flood control and irrigation. An openly conducted National Water Plan exercise was very helpful in bringing out these conflicts, giving fisheries greater prominence and priority within government. One of the reasons why the importance of fisheries to different sectors of the community has not been emphasised has been the difficulty in measuring benefits in ways compatible with conventional cost-benefit analysis. With the recent attention on the environment there is better recognition of the importance of exploiting the diverse opportunities in aquatic systems and stronger economic arguments for fisheries investments. The question of drawing drinking-water supplies from water used for aquaculture depends on the intensity of use; highly intensive aquaculture will give poor quality water. In the case of fish cultured in wastewater, information about how toxins and pathogens move through fish and therefore the safety risks to consumers is available. The highly intensive form of food production in which fish ponds, vegetable production and pig keeping are integrated was discussed. Integrated fish farming can typically produce 2-8 tons/ha/year of fish provided it fits in to the physical and organisational aspects of the farming system. However, there are difficulties of unutilised waste matter accumulating in the pond.

PAPER 14

Managing systems not uses: the challenges of water-borne interdependence and coastal dynamics

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Summary: Development which is focused on single uses of a system may lead to resource use conflicts, foreclose on other options and result in suboptimal and non-sustainable use. To justify multiple-use management, full economic analysis incorporating values of non-marketed on-site and off-site goods and services of ecosystems are required. Multi-disciplinary research is needed to assign such values. Water-borne interdependence of coastal ecosystems make it difficult to isolate areas for management purposes. Alterations to water (and associated suspended sediment, dissolved nutrient, etc.) flows within or between systems are generally detrimental to existing ecosystems. The water connections do however make it theoretically possible for protected areas to generate benefits over extensive areas. However, there are few data to support such a contention and the scientific basis for establishing marine reserves needs to be evaluated critically. The implications of rising sea level for coastal areas have been much discussed recently but in coastal developing countries, including low-lying atoll states which are extremely vulnerable, it appears that coastal management problems generated by burgeoning populations and ill-conceived coastal developments are the most important issues at present.

INTRODUCTION

Three major challenges to those involved in coastal zone or coastal resources management are: (a) implementing the concept of multiple-use management of systems to derive long-term sustainable benefits for the maximum number of people; (b) recognising the problems of water-borne interdependence of coastal ecosystems and in special cases making use of this interdependence; and (c) dealing with the problems of trying to manage such dynamic systems and the likely exacerbation of these problems by predicted sea-level rise as a result of global warming. In the limited time available I would like to consider very briefly a few aspects of these challenges and identify a few areas where research might be directed.

MULTIPLE-USE MANAGEMENT

Management of the coastal zone has tended to be piecemeal (project, sector, or single-use orientated) but coastal systems have a high level of interdependence, largely because of the water which links them. Development or management focused on single uses or activities often has negative impacts on other potential or actual uses of a system, may lead to resource use conflicts and generally results in suboptimal use of the system. As an example of a coastal ecosystem which may be optimally exploited by sustainable multiple-use management I will look at mangroves. Coral reefs or seagrass beds might equally well be used as examples.

Mangroves are an example of an ecosystem which has suffered particularly badly from development with 55% of original area reported lost in the Afrotropical realm and 58% in the Indonesian realm in 1986 (World Resources Institute, 1990). This has stemmed both from a sectoral approach to resource management and a failure to recognise the multiplicity of goods and services provided by mangroves. The 'Mangrove Area Management Handbook' (Hamilton and Snedaker, 1984) lists over 70 direct and indirect products and services provided by mangroves. Examples include: timber for construction, firewood, charcoal, medicinal compounds, alcohol, honey, shellfish, nursery and feeding grounds for finfish and shrimp, control of coastal erosion, protection of inland areas from storm surges and wind damage, and protection of offshore systems such as coral reefs from excessive nutrients and sediments from inland agriculture. Despite these multiple uses, and perhaps because most of the uses are on an artisanal scale and thus contribute to the local subsistence economy rather than national commercial interests, mangroves have in the past been regarded as 'wastelands' ripe for sectoral development by forestry, aquacultural or agricultural sectors. Sustainable mangrove forestry requires careful management and does not necessarily exclude other uses. On the other hand, wholesale conversion to fish or shrimp ponds, to salt production, or to rice paddies forecloses on other use options and may cause loss of valuable services such as coastal protection (e.g. in Java where a protective mangrove fringe is seldom left) and provision of shrimp and finfish nursery areas to sustain local capture fisheries.

An analytical framework for assessing the economics of preservation, multiple use ('utilisation') or conversion to single use (or destruction) of mangroves have been discussed in detail by Hamilton and Snedaker (1984). Figure 1 shows the relation between location (on-site/off-site) and type of mangrove goods and services (marketed/non-marketed) and traditional economic analysis. There are still uncertainties and difficulties in the valuation of quadrants 2, 3 and 4 which need to be resolved and are discussed below.

FIGURE 1
Relationship between location and valuation of goods and services derived from mangroves

		Location of goods and services	
		On-site	Off-site
Valuation of goods and services	Marketed	1 Usually included in an economic analysis (e.g. poles, charcoal, woodchips, mangrove crabs)	2 May be included (e.g. fish or shellfish caught in adjacent waters)
	Non-marketed	3 Seldom included (e.g. medicinal uses of mangrove, domestic fuelwood, food in times of famine, nursery area for juvenile fish, feeding ground for estuarine fish and shrimp, viewing and studying wildlife)	4 Usually ignored (e.g. nutrient flows to estuaries, buffer to storm damage)

Source: Hamilton and Snedaker, 1984

The Asian Wetland Bureau indicates that in Malaysia mangrove systems contribute some $ 800 million to the national economy in terms of the marine fisheries they sustain. Martosubroto and Naamin (1977) show a correlation between shrimp catch and area of mangrove swamp remaining in various parts of Indonesia. In Fiji approximately 60% of commercially important coastal fishes are either caught or spend part of their life-cycle within mangrove areas. Lindall (1973) estimated that in Florida 80% of all marine species of commercial or recreational value are dependent upon mangrove estuarine areas for part of their life-cycle. However, Thollot (1992) working in New Caledonia pointed out that most reef fish juveniles found in mangroves also occur in other coastal habitats. As in many other areas of coastal management the scientific evidence for the importance of mangroves to both finfish and shrimp fisheries is somewhat equivocal and qualitative. Few scientists doubt their importance as nursery and feeding areas to many marine species but questions remain as to (a) which marine species absolutely require mangroves to complete their life-cycles and maintain populations, and (b) how much mangrove is necessary to sustain capture fisheries deemed dependent on them.

Similarly the storm-protection role of mangroves appears generally accepted. For example, areas where mangroves have been destroyed in Bangladesh appear to suffer greater damage and loss of life than those where the mangroves survive and provide some protection of areas inland, but again little quantitative information seems to be available which would allow monetary values to be placed on this service. There are difficulties in that the value of the service will depend on the value of the land being protected, and if the adjacent land is developed the value of the mangrove area as building land may increase so that it becomes cost-effective to destroy it and also construct sea defences. Leaving a belt of mangroves to stabilise and protect coastlines which are being developed is generally considered sensible, but the relative effectiveness of belts of different thicknesses under different climate regimes does not yet appear to have been modelled. Coastal managers need such information or at least some guidelines on which to base decision making.

In summary, the optimal use of an ecosystem is likely to be through multiple-use management (i.e. utilisation of the full range of goods and services provided in a sustainable way). This is likely to provide least social disruption, greater equity, and greatest long-term economic benefits to society and it does not foreclose other options for use at a later date. However, it may not be seen as 'development' by politicians and is unlikely to be attractive financially to commercial interests wishing to exploit the resource base for single uses. At present multiple-use management is perhaps more of a concept than a reality but a powerful one which can be used to draw attention to the alternatives to wholesale conversion or destruction. Multi-disciplinary research still needs to be done to attach figures to the economic value of non-marketed on-site and off-site goods and services provided by ecosystems. There is a case for more direct involvement of economists with scientists and engineers in such research.

WATER-BORNE INTERDEPENDENCE

The ebb and flow of the tides, longshore currents, wave action, land drainage, surface runoff and riverine outflows act to link coastal ecosystems such as mangroves, beaches, marshes, seagrass beds, estuaries and coral reefs both with themselves and with distant areas such as upland watersheds. This intimate linking of coastal systems by water has important implications with respect to management. These implications may make management more difficult. Two examples are:

- It is difficult to isolate areas for management purposes, thus external factors or activities outside of a manager's control can render his local efforts futile. This should be borne in mind when boundaries are assigned to managed areas.
- Significant alterations to water flows within or between systems are generally detrimental.

An example of the encroachment of external influences can be seen in one of the largest mangrove reserves in the world, the Everglades of Florida where *c.* 100 000 ha of mangrove are protected. Elevated phosphorus levels released in drainage waters from agricultural areas to the north are causing changes in plant and wildlife communities within the National Park (Maltby, 1991) and there is also some concern about pesticide levels. Similarly, the character of the Indus delta which used to prograde at about 30 m per year has been so altered by upstream barrages and damming for irrigation purposes that it is no longer a suitable habitat for most of the mangrove species which once grew there luxuriantly. Freshwater flow has been drastically reduced and sediment discharges are about one quarter of what they were and still decreasing. External factors have changed the character of the coastal habitat so that it can no longer support the ecosystems it once did and productivity of the whole delta area is declining. Eastern Mediterranean fisheries and the future of the Nile delta have similarly been markedly affected by building of the Aswan High Dam hundreds of miles inland.

Interruptions or disturbances to water flows take the form of dams, barrages, jetties, breakwaters, causeways, roads, groynes, canals, etc. Such structures often upset delicate balances among coastal systems. Alteration in salinities in mangrove areas as a result of solid causeway construction can lead to mangrove death as has occurred in parts of the Yucatan for example, while changes in hydrological conditions in lagoonal areas such as that caused by dams or canalisation can lead to reduced productivity and damage to fisheries (e.g. Iguape-Paranagua lagoon system in Brazil). Solid causeways built between atoll islands in Addu Atoll in the Maldives have exacerbated erosional problems by blocking sediment transport from outer reef flats to the lagoon-side of islands. This has led to sediment build-up on the outside of the blocked channel and accelerated erosion of beaches primarily on the lagoon-side, driven by long shore currents (Kenchington, 1985). Various other examples of the consequences of disturbing sediment transport along beaches and engineering solutions to the problems created are discussed by Hayes (1985).

On the positive side is the implication that protected areas or reserves may have effects over quite wide areas. Thus relatively small circumscribed mangrove or coral reef reserve areas may, for example, sustain fisheries over extensive areas by, on the one hand, providing nursery grounds and, on the other, maintaining adult spawning stocks in the face of heavy fishing pressure elsewhere. The idea is seductive and it is perhaps easier politically and administratively to designate restricted marine reserve areas and control access and use of these than to enforce other management measures over wider areas. Whatever the reasons, such areas are currently in vogue as management options with strong support form the conservation lobby. As usual the science is lagging behind but recent work looking at the fishery implications of marine reserves clearly indicates significant increase in numbers and average size of commercially important fish in reserve areas compared to unprotected areas where fishing pressure is significant (Bohnsack *et al.*, 1992; Roberts and Polunin, 1991). In the Sumilon Island reserve in Philippines, loss of reserve status in one year led to a quartering of the stocks of the main group of fish being exploited (Caesionidae). Numbers recovered a few years after reserve status was re-established (Russ, 1992). There is some evidence that fishermen catch more in the vicinity of reserve areas that in areas distant from them but quantitative evidence of: the range of effects; the percentage of a habitat which needs to be preserved for benefits to be observed; and the level of fishing pressure required outside of protected areas for them to be likely to have any noticeable effect on recruitment, is lacking. Russ (1992) suggests that the proposed closing of 5% of the Great Barrier Reef and 20% of the US South Atlantic shelf to line fishing is likely to have benefits in terms of enhanced larval supply. Such options are unlikely to be available in many developing countries closely dependent on these resources for protein.

COASTAL DYNAMICS, ANTHROPOGENIC DISTURBANCES AND RISING SEA LEVEL

Coasts are very dynamic systems with vast amounts of energy being dissipated at the land-sea interface. The predicted acceleration in the rate of rise of global mean sea level from about 1.2 mm/year to a 'best guess' of 4.5 mm/year (recently revised downwards from 6 mm/year, Wigley and Raper, 1992) under the IPCC 'Business-as-Usual' scenario (Warrick and Oerlemans, 1990) and possible increases in storm power and/or frequency are likely to make coastal areas more dynamic and unstable and put much infrastructure at risk of inundation. Human society requires various structures to be sited on the coast for reasons of transport, availability of sea water or estuarine water for cooling or waste disposal, recreation (hotels, holiday homes), access to coastal resources, etc. Because of the dynamic nature of the majority of coasts and the static nature of the structures, this often creates problems. Interestingly, while rising sea level is perceived as a major problem with vast economic costs in sea defence or relocation in the next century for developed countries, most developing nations appear more concerned with immediate coastal management problems.

Among countries particularly at risk in the face of rising sea level are low-lying atoll states such as Tuvalu and Kiribati in the Pacific and the Maldives in the Indian Ocean. Since President Gayoom of the Maldives has helped instigate much debate on sea-level rise both in the UN and in the Commonwealth Secretariat, I thought it might be useful to look at the problems facing his country, dubbed as one of the 'first-to-go' by the popular press.

The nation is entirely low lying with no point of land much more than 500 m from the sea and with its human habitation, industry and vital infrastructure all within 0.8-2.0 m of mean sea level. The sandy islands, about 1300 of which make up the archipelago, undergo seasonable cycles of erosion and deposition with the changing monsoons which underlines the dynamic nature of the equilibrium which permits their existence. The dynamic nature and fragility of the islands is shown by historical records which indicate that some 50 islands have been wholly or partly washed away and 40 have suffered inundations, often repeatedly (Maniku, 1990). Accretion processes are also at work and about 50 islands are reported to have been joined by the build-up of sandbanks between them. In a recent swell wave incident which causes inundation and erosion at the capital island Male in April 1987 (and also played a large role in stimulating local concern about both the environment and sea-level rise), sediment was at the same time piled up on a submerged reef to create the island of Udhafushi in North Male Atoll. This island is now surrounded by a rapidly developing fringing reef and had vegetation on it in 1989. Two points I would like to stress are: (a) on these islands the dynamic equilibrium is very delicate and little disturbance is required to generate coastal management problems, and (b) the only areas of Male inundated by the swell wave incident in 1987 were those which had been 'reclaimed' from the sea. To protect 1.52 km length of coast in front of a 60 ha reclaimed area, which lies on top of what was previously the ocean side lagoon and reef flat of the island, some US$ 14 million has been spent on detached breakwaters courtesy of the Japanese International Co-operation Agency.

The vertical growth of coral reefs which provide the main sea defence of the islands is considered likely to be able to keep up with a sea-level rise of 4-5 mm/year (Buddemeier and Smith, 1988). However, it is still not known at what rate biogenic sediments are generated on the reefs and thus it is unclear whether lagoons behind fringing reefs will get deeper and alter beach profiles or fill at the same rate as sea-level rises and maintain beach profiles. Without such knowledge it is difficult to predict how vulnerable the islands will be to sea-level rise.

Although the Maldives are clearly at risk in a world of rising sea level, over the next 25 years it is clear that their major problems are ones of coastal management arising from coral quarrying, groundwater over-abstraction leading to salinisation, erosion due to solid causeway constructions between islands, and 'reclamation' (infilling of reef and lagoon areas) to increase land areas of over-populated islands. These local anthropogenic disturbances are of immediate concern although in the longer term they will make the Maldives more vulnerable to sea-level rise.

In a wide range of developing countries it seems that rates of anthropogenic degradation of coastal resources and the problems of how to manage these resources in the face of increasing use and increasing conflicts are seen as the critical problems beside which problems associated with global warming and sea-level rise are of little immediate significance.

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DISCUSSION

In respect to coastal reefs it was pointed out that the ODA has been extensively involved in helping with erosion and coral mining studies for the Maldives with over £1 million being spent. However, there is still disagreement between experts about causes and solutions. The traditional coral mining technique used in the Maldives is to trim off the top of the reef but the reef does not recover and a means of rehabilitation has not been identified. An alternative theory would be to take an uninhabited reef down by 10 m, providing 50 years' supply of aggregate and, being submerged, the coral would then rebuild. On the subject of mangroves it was pointed out that they are an ecological succession creating land. In the management of mangroves one has to consider the roles of a range of species and the challenge is to maintain the ecological succession. A comment was made on the Sundarbans mangrove forest in Bangladesh which is not very biodiverse, consisting of very specialised species yet it produces a wide range of products several of which have been valued in terms of cash and employment (such as prawns). Mangrove replanting schemes were reported from Maldives, Pakistan and Vietnam. A mangrove rehabilitation scheme in Pakistan is using different species from the original ones since salinity levels have changed; in Vietnam a successful mangrove replacement programme has resulted in increased supplies of fish in markets. The problems over the declining freshwater lenses in atolls was raised; these may be destroyed long before the atolls are submerged by rising sea level. In Male the freshwater lens is almost non-existent being at most only 5 m deep; this occurred mainly due to the installation of a freshwater sewage system. It was suggested that the value of the coastal protection works ($ 14 million to protect 60 ha of land in the case of Male) might reflect the protection value of mangrove or the original coral reef.

PAPER 15

World food production: the past, the present and the future

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Summary: The paper examines why growth in agricultural production is now slowing and whether present-day intervention measures are capable of reversing this trend. It is argued that the present methodology used to identify potential development projects is unsatisfactory, and as a result many projects fail because they do not address the key issues that limit productivity of the farms. It is further argued that if we are to halt the decline we must therefore adopt a more systematic approach to discovering the key bottlenecks in the agricultural sector. This would then allow the most appropriate intervention measures to be identified. An alternative planning framework is suggested for the agricultural sector that could lead to the development of a better method for identifying effective intervention measures.

PAST SUCCESS

In the past 30 years world food production has undergone an unprecedented rate of growth, largely enabling agriculture to meet the needs of the rapidly growing population of most countries outside Africa. This success story is in contrast to the trends in the preceding years, when increases in production could not meet the expanding demand for food.

This success story has resulted from a number of key factors which combined to give an unprecedented increase in production:

- New lands were brought into production by the rapidly expanding population. In all countries this has traditionally been the main way of producing more food to feed a growing population and, in most cases, when land is plentiful this provides an economic solution. Unfortunately, with the increased pressure on land, new farmers are forced on to more marginal land, resulting in a rapid degradation of much of the world's soil resource, our short-term success being partly at the expense of long-term sustainability.
- The introduction of short straw, disease tolerant varieties of wheat and rice, capable of responding well to artificially high levels of fertility.
- The rapid expansion in area of irrigated land, with its potential to produce consistently high yields, has played a significant role in increasing agricultural production during this period; the area of irrigated land now being some 220 million hectares.
- Increased use of agrochemicals.
- Increased mechanization.

Although there are other contributing factors that have been important for increasing the production of specific crops and in solving problems occurring in unique locations, there can be little doubt that the above mainly account for the unprecedented success of agriculture in the last 30 years. The relative importance of each of the above factors differs from country to country depending on local conditions, and where one or more of these variables have proved limiting or inapplicable they have been unable to benefit from the so-called 'green revolution'. For example, sub-Saharan Africa has not been able to benefit significantly since wheat and rice are not the staple food crops, and surface water supplies suitable for irrigation are restricted.

Clearly, despite the overall success story we have had significant failures and we need effective intervention measures to overcome the production constraints in many countries, particularly in Africa. We must also consider if this unprecedented rate of growth in agricultural production can continue.

WHERE ARE WE NOW?

A nation's land and water resources are finite and in many countries these resources are becoming fully utilized and, hence, the potential for further extensive expansion of agriculture is limited, with farmers already developing the more marginal lands and utilizing poor quality water for irrigation.

Improved agricultural inputs, the so-called 'green revolution' technologies, have enabled farmers to utilize the land more intensively and to obtain better crop yields the technology being particularly important in those countries dependent on wheat and rice. From a slow beginning in the early 60s the technology has been increasingly adopted, and in most countries farmers are now aware of the benefits to be gained from it. During this period nearly all farmers throughout the world have progressively adopted the practices which they find to be beneficial in their own environment, have modified others such as the recommended levels of fertilizer to their own socio-economic circumstances, and rejected others. As a result in many countries the unprecedented rate of growth is now slowing, and in others it has stopped, despite the fact that in many countries yields are still at a fairly modest level.

Pakistan is a good example of a nation that has benefited significantly from all these intervention measures, enabling it to feed its rapidly growing population (growing at 3.1% per year). Unfortunately, this impressive rate of growth has slowed in the past 10 years, with the yield of the major food crops remaining fairly static; increased production resulting from an increase in the irrigated area (Table 1). Nevertheless, yields remain relatively low and if present trends continue Pakistan will move from having a grain surplus to an annual deficit of 23% by the year 2000, and a 30% shortfall by the year 2012. Large deficits are also predicted for other crops[1]. In the years of rapid expansion growth was largely achieved by a progressive increase in irrigated area and by the gradual introduction of new varieties and the use of fertilizer. Production is now levelling off as water resources become fully utilized and as farmers both plant improved varieties and apply levels of fertilizer that they find attractive. Although there is some scope for further production from irrigating more land, the availability of water is likely to pose a major obstacle to further large-scale development of land. As with many countries, if they are to increase agricultural production to meet the needs of a growing population they must achieve more intensive production on existing farmland and use water resources more wisely. The potential to double or more these existing low yields exists, and the technical know-how to achieve this is available and relatively simple, unfortunately as in many other cases the technology proves to be inapplicable because of constraints in the farming system. The result is that we do not know what intervention measures might bring about a significant increase in production, nor do we have a rational approach to identify what the true bottlenecks are and how we might overcome them.

The example is fairly typical of many countries which achieved rapid growth in agricultural production in the past but which are predicted to have severe difficulties in meeting the growing needs of their population unless they find appropriate intervention measures for their farming systems. Unfortunately, all too often many governments try to overcome the problem by developing investment strategies to increase production which are founded on political will or unreliable analysis, with little or no analysis of the sector as a whole. A clear case of this is to be seen in Egypt where scarce financial and water resources are being used to irrigate impoverished sand to grow wheat in the desert.

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[1] Water Sector Investment Plan (1990-2000) Water and Power Development Authority

TABLE 1
Wheat and rice production in Pakistan

Harvest year	78	79	80	81	82	83	84	85	86	87	88
Yield (t/ha)											
Wheat	1.3	1.5	1.6	1.6	1.6	1.7	1.5	1.6	1.8	1.6	1.7
Rice	1.6	1.6	1.6	1.6	1.7	1.7	1.7	1.7	1.6	1.7	1.7
Irrigated area of crop						1977			1978		
(million ha)						10.2			11.6		

CAN INVESTMENT STRATEGIES REMOVE THE BOTTLE-NECKS IN AGRICULTURAL PRODUCTION OF THE WORLD?

The key intervention measures outlined above provided a simple broad-brush approach to agricultural development with new widely applicable technologies being readily transferred from country to country. Although the approach has had great success it is clear that it has been far more effective in some countries than others, depending on the relevance of the technology to the local environment. The development sector appears to feel that because of the general success of this broad-brush approach a similar strategy can be followed for the implementation of a wide range of possible intervention measures. The result has been a tendency to take the success of a project in one country as a basis to justify the implementation of projects of a similar nature across the globe, with agencies tending to follow each other in investing in projects of a similar nature at any one particular time, the so-called 'bandwagon effect'. Listed below are some of the areas that have been favoured for investment at various times during the past 20 years, they come and go, often having little long term impact:

- Fertilizer subsidies
- Integrated rural development projects
- Extension
- T and V extension systems
- Irrigation
- Dryland agriculture
- Small-scale projects
- Large-scale projects
- Rural credit banks
- On-farm water management
- Financial restructuring of the economy
- Adaptive research
- Sector-based education.

and more recently:

- The environment
- Women
- Good government
- Project-based training.

There appear to be a number of ways new bandwagons are initiated. They may be based on a very successful project in a specific location or result from a combined political will for projects in a specific area; they can arise from a desperation to try to do something new that might work. There is nothing wrong with any of these and it is well worth trying new ideas on an experimental basis. The problem occurs when the need to spend large amounts of money with the least administrative costs results in the experiments becoming large projects which are rapidly replicated as the bandwagon begins to roll.

On mentioning these reservations to a banker in the aid sector the reassuring reply was that there is no need to worry because all projects undergo thorough economic analysis and have to be 'bankable', giving an internal rate of return of at least 12%. Although the discounted cash-flow techniques used for economic assessments provide an accepted procedure for comparing the viability of projects, the results can only be justified if the assumptions on which they are based can be justified. Unfortunately, all too often this is not the case, and on close examination the economic viability of a project is often pivotal on a number of professional judgments which the evaluation team has had to make. Given that in most developing countries we do not know with any level of certainty what the underlying bottlenecks in the agricultural sector are, nor the magnitude of the effects, many of our judgments must be considered open to question. Further, in the development business we are all being asked to formulate and evaluate projects in an ever decreasing amount of time, giving little opportunity for us to understand truly the complexity of the agricultural sector of a country for which we are formulating investment polices. We therefore put forward for discussion the idea that the level of uninformed judgment that is required to formulate many agricultural development initiatives largely invalidates much of our economic analysis, with the result that in many countries, despite vast investment in the agricultural sector, production continues to stagnate. We all start out as optimists, not realizing that optimists and pessimists are the same thing except that the latter are better informed.

The international hotels of all developing countries are full of 'experts' in the development industry, all trying to improve the performance of the agricultural sector, but with none of us fully understanding the key issues that are causing the bottlenecks in the system. We readily fall back on the well-used phrase "in my opinion" to make up for lack of facts; the result is that in all too many of our decisions are too subjective. As a result many development initiatives are based on preconceived ideas with little understanding of the multifaceted and complex systems which interact to control production on the farms. Hence, projects end up not addressing the real constraints that exist in a given agricultural system, simple because these constraints have not been recognised.

On asking a wide range of staff connected with a large irrigation system, from the minister to the smallest farmer, "why are yields so low and where should money be invested to increase productivity?", every person identified a different cause and a different solution depending on our personal perspective of the project. In reality we had all identified many symptoms but not necessarily the underlying cause of the problems.

This week's conference has brought together a large group of informed expertise from within engineering and natural resources with a brief to combine the expertise of the two disciplines to enable us to explore where irrigation fits into the agricultural sector and where it should be going in the light of such important issues as global warming and desertification. Depending on our outlook we expound the virtues of different development strategies such as the need to protect the environment, the benefits of small schemes, of large schemes, the role of NGOs and of the cost/benefit of irrigation development as compared with investment in dryland agriculture. The reality is that all have their appropriate time and place; the skill is determining when and where it is.

It is argued therefore that if agriculture is to meet the needs of the world in the next 30 years we will need to develop a more systematic approach to identifying the key constraints in the agricultural systems of the world to enable us to target our aid much more effectively. Such an approach would supersede the need for debates like "Are large irrigation projects better than small? Should irrigation be favoured at the expense of dryland agriculture?".

A LOOK AT POSSIBLE FUTURE INVESTMENT STRATEGIES

Value for money is essential when aid money is targeted at the poorest people on earth. Unfortunately, in recent years it has become more and more difficult to target aid effectively in the agricultural sector. All too frequently money has been spent on projects that have not removed the key constraints in the agricultural sector and it is clear that if aid is to be more cost-effective in the future it must be targeted at the key bottlenecks.

There appear to be two main potential investment strategies which could focus investment into effective projects.

- To identify a number of key constraints which are known to limit production in many countries, but to which we do not readily have solutions, and concentrate a large proportion of the aid money into developing solutions. This is a high-risk strategy and projects would need to have the potential for very high returns. Such a strategy might result from a feasibility study to evaluate the technical possibility of genetically engineering cereals to enable them to live with symbiotic bacteria for nitrogen fixation. If such a programme were estimated to have only a 50% chance of success it could be argued that the potential benefits could justify spending a large proportion of the world's total aid budget on it. Such high-risk high-gain strategies are unlikely to prove attractive to donors for a number of reasons but they do have many attractions, not least the size of the potential benefits.

- If the managers of a car plant decide that they want to increase production they do not just make investment in the different areas of the production process and hope that it will remove the bottlenecks that will allow increased production. They carry out detailed analysis of the production system to enable them to identify the constraints and the investment needs that will allow them to increase production. Further production constraints are progressively identified until a level of investment is identified that will allow them to reach production targets, i.e. until marginal costs exceed marginal benefits.

Within the agricultural sector of most countries such an approach is not considered. Indeed in many countries the agricultural production system is often directed from within two separate ministries, irrigation and agriculture. There is often both an irrigation sector five-year plan and an unrelated agricultural sector plan. Detailed examination of a number of such plans from several countries indicates that there is normally no rational basis for the plan but that they are made up of a mixture of the aspirations of the civil servants and the wishes of the politicians. In reality at the end of the planning period they prove to have been little more than a work of fiction. These poorly thought out plans are used to identify the investment opportunities for development agencies and form the basis for requests for aid and/or soft loans.

We clearly need to move towards a more rational planning process in a similar systematic fashion to that used in manufacturing industry. The World Bank carries out regular sector reviews, as do many aid agencies, but these fall far short of a full analysis of a country's agricultural sector in which the key bottlenecks are identified and quantified.

Many agricultural researchers have recognized that if they are to produce research results that meet the farmers' needs they must adopt a systematic approach to identify on-farm constraints, thus enabling them to identify their research priorities. The analytical techniques that they have developed are proving powerful tools and it is logical that such a systematic approach should be extended to enable us to identify the true bottlenecks in a nations agricultural sector; thus enabling investment to be targeted accurately.

This approach implies a rigorous, quantitative and systematic effort, first to understand the farming operation, and then proceeding to define and develop an appropriate investment strategy. Farming systems need to be analysed in their entirety to establish which of the multitude of variables impinging on farm activities are the main causes of low productivity. This appears to be the only way to identify which constraints need to be removed, if it is possible to remove them, and how.

For this analysis the farm population needs to be disaggregated by such factors as agroclimatic zone, size, tenure systems and the availability of water. The effect of social issues need to be quantified. The economics of the farming practices of the disaggregated farms need to be fully understood. Analysis is largely possible through statistical and survey techniques developed by farming systems researchers and others. Such farm-level models, however, have severe limitations if used in isolation and the analytical approach has to be extended to examine the constraints that exist in domains outside the farm. It is at this level that the approach is likely to need further refinement.

Such a systematic approach to analyse the agricultural sector of a country would bring together the skills of all the disciplines involved in effective agriculture development to produce a comprehensive reference document on the state of a nation's agriculture. Such documents would adopt a systematic approach to analyse the agricultural sector, starting from identifying issues that affect the production of individual crops and management of a farm's resources, to studies of the potential to utilise further the nation's resources in the political and economic climate of a country. It is expected that such a document would be updated annually and act as reference work to provide analysed data for the further development of agricultural sector plans; both for the effective identification of projects and also to improve project formulation.

Although such a systematic approach is needed in many countries it is suggested that the methodology should be fully developed and tested in one country. If successful it would then act as a blueprint for use in other appropriate environments.

DISCUSSION

It was pointed out that a conclusion made at a conference held at Wye College two years ago was that targeting aid at the emergent commercial farmers was more likely to produce substantial benefits than attempting to target the poorest but ODA policy has continued to overlook this conclusion. It was argued that it is not a question of choosing between the top-down scientifically driven strategy or the site-specific bottom-up approach analysing constraints on farmers but both should be pursued. In discussion over possibilities of further dramatic increase in yields in South Asia it was argued that good use of water was the key. It was stated that we are on the verge of breaking major scientific barriers to higher yield, such as the photosynthetic barrier, but crop yields of up to 6 tonnes/ha, though easily achievable, were rarely being attained in the developing world, well below the 10-20 tonnes/ha set by the photosynthetic limit. It was added that the major issue is not so much the upper limits to achievable yields but the yield gap between average farmers and poor farmers. Under-yielding is a problem common to many industries besides agriculture. It was argued that there are common socio-political problems which donors attempt to address through influencing policy. The concept of 'yield per unit of water evaporated' was suggested as a useful criterion. It was recognised that improvements in water-use efficiency could be made but also that excess water passes into the groundwater and is re-used. Despite the importance of fish in diets (up to 90% of animal protein consumed in Bangladesh) many of the benefits of increased rice production are lost through decline in fish catches due to irrigation practices. It was suggested that proponents of irrigation needed to take a wider perspective but also pointed out that experience in India shows that aquaculture and rice irrigation can go hand in hand.

PAPER 16

Climate change and the future of agriculture

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Summary: The purpose of this paper is to review our current knowledge of the potential effects of climate change on agriculture and world food supply. Attention is first directed to the types of climate change, particularly reductions in soil water availability, likely to be most critical for agriculture. Secondly, a number of types of effects on agriculture are considered: 'direct' effects of elevated CO_2, shifts of thermal and moisture limits to cropping, effects on drought, heat stress and other extremes, effects on pests, weeds and diseases, and effects on soil fertility. Thirdly, a summary is presented of likely overall effects on crop and livestock production. The conclusion is that, while global levels of food production can probably be maintained in the face of climate change, the cost of this could be substantial. There could occur severe negative effects at the regional level. Increases in productive potential at higher latitudes are not likely to open up large new areas for production. The gains in productive potential here are unlikely to balance possible reductions in potential in some major grain-exporting regions at mid-latitudes.

INTRODUCTION

This review considers, firstly, those systems, sectors and regions of agriculture that are most sensitive to anticipated changes of climate that may result from emissions of greenhouse gases, primarily carbon dioxide. Secondly, it summarises present knowledge about the potential socio-economic impact of changes of climate on world agriculture. Thirdly, it considers the adjustments in agriculture that are most likely to occur. Finally, it establishes research priorities for future assessments of impact.

THE MOST SIGNIFICANT ASPECTS OF CLIMATIC CHANGE

The potentially most important changes of climate for agriculture include: changes in climatic extremes; warming in the high latitudes; poleward advance of monsoon rainfall; and reduced soil water availability (particularly in mid-latitudes in midsummer, and at low latitudes).

Climatic extremes

It is not clear whether changes in the variability of temperature will occur as a result of climate change. However, even if variability remains unaltered, an increase in average temperatures would result in the increased frequency of temperatures above particular thresholds. Changes in the frequency and distribution of precipitation are less predictable, but the combination of elevated temperatures and drought or flood probably constitutes the greatest risk to agriculture in many regions from global climate change.

Warming in high latitudes

There is relatively strong agreement among GCM predictions that greenhouse-gas induced warming will be greater at higher latitudes (IPCC, 1990). This will reduce temperature constraints on high-latitude agriculture and increase the competition for land here (Parry and Duinker, 1990). Warming at low latitudes, although less pronounced, is also likely to have a significant impact on agriculture.

Poleward advance of monsoon rainfall

In a warmer world the inter-tropical convergence zones and polar frontal zones might advance further poleward as a result of an enhanced ocean-continent pressure gradient. If this were to occur then total rainfall could increase in some regions of monsoon Africa, monsoon Asia and Australia, though there is currently little agreement on which regions these might be (IPCC, 1990). Rainfall could also be more intense in its occurrence, so flooding and erosion could increase.

Reduced soil water availability

Probably the most important consequences for agriculture would stem from higher potential evapotranspiration, primarily due to the higher temperatures of the air and the land surface. Even in the tropics, where temperature increases are expected to be smaller than elsewhere and where precipitation might increase, the increased rate of loss of moisture from plants and soil would be considerable (Parry, 1990; Rind *et al.*, 1989). It may be somewhat reduced by greater air humidity and increased cloudiness during the rainy seasons, but could be pronounced in the dry seasons.

TYPES OF EFFECT ON AGRICULTURE

There are three ways in which increases in greenhouse gases (GHG) may be important for agriculture. Firstly, increased atmospheric carbon dioxide (CO_2) concentrations can have a direct effect on the growth rate of crop plants and weeds. Secondly, GHG-induced changes of climate may alter levels of temperature (as well as temperature gradient), rainfall and sunshine and this can influence plant and animal productivity. Finally, rises in sea level may lead to loss of farmland by inundation and to increasing salinity of groundwater in coastal areas.

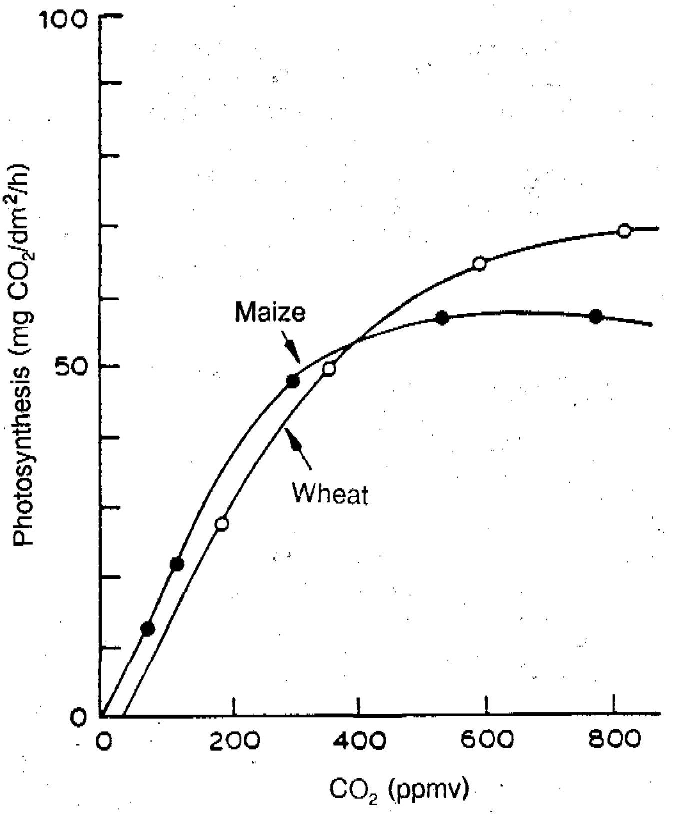
Effects of CO_2 enrichment

- Effects on photosynthesis

Carbon dioxide is vital for photosynthesis, and the evidence is that increases in CO_2 concentration would increase the rate of plant growth (Cure, 1985; Cure and Acock, 1986). There are, however, important differences between the photosynthetic mechanisms of different crop plants and hence in their response to increasing CO_2. Plant species with the C3 photosynthetic pathway (e.g. wheat, rice and soybean) tend to respond more positively to increased CO_2 because it tends to suppress rates of photorespiration. However, C4 plants (e.g. maize, sorghum, sugar-cane and millet) are less responsive to increased CO_2 levels (Figure 1). Since these are largely tropical crops, and most widely grown in Africa, there is thus the suggestion that CO_2 enrichment will benefit temperate and humid tropical agriculture more than that in the semi-arid tropics. Thus, if the effects of climate changes on agriculture in some parts of the semi-arid tropics are negative, then these may not be partially compensated by the beneficial effects of CO_2 enrichment as they might in other regions. In addition we should note that, although C4 crops account for only about one-fifth of the world's food production, maize alone accounts for 14% of all production and about three-quarters of all traded grain. It is the major grain used to make up food deficits in famine-prone regions, and any reduction in its output could affect access to food in these areas (Morison, 1990).

The C3 crops in temperate and subtropical regions could also benefit from reduced weed infestation. Fourteen of the world's 17 most troublesome terrestrial weed species are C4 plants in C3 crops. The difference in response to increased CO_2 may make such weeds less competitive. In contrast, C3 weeds in C4 crops, particularly in tropical regions, could become more of a problem, although the final outcome will depend on the relative response of crops and weeds to climate changes as well (Morison, 1990). Many of the pasture and forage grasses of the world are C4 plants, including important prairie grasses in North America and central Asia and in the tropics and subtropics. The carrying capacity of the world's major rangelands are

FIGURE 1
Typical photosynthesis response of plants to CO_2



Notes: Net photosynthesis of wheat is about 70 mg $CO_2/cm^2/h$ compared with maize (about 55 mg $CO_2/cm^2/h$) for equivalent light intensity (0.4 $cal/cm^2/min$). Maize is saturated at a lower CO_2 concentration (*c.* 450 ppmv) than wheat (*c.* 850 ppmv)

Source: Adapted from Akita and Moss, 1973

thus unlikely to benefit substantially from CO_2 enrichment (Morison, 1990). Much, of course, will depend on the parallel effects of climate changes on the yield potential of these different crops. The actual amount of increase in usable yield rather than of total plant matter that might occur as a result of increased photosynthetic rate is also problematic. In controlled environment studies, where temperature, nutrients and moisture are optimal, the yield increase can be substantial, averaging 36% for C3 cereals such as wheat, rice, barley and sunflower under a doubling of ambient CO_2 concentration. Few studies have yet been published, however, of the effects of increasing CO_2 in combination with changes of temperature and rainfall.

Little is also known about possible changes in yield quality under increased CO_2. The nitrogen content of plants is likely to decrease, while the carbon content increases, implying reduced protein levels and reduced nutritional levels for livestock and humans. This may, however, also reduce the nutritional value of plants for pests, so that they need to consume more to obtain their required protein intake.

- Effects on water use by plants

Just as important may be the effect that increased CO_2 has on the closure of stomata. This tends to reduce the water requirements of plants by reducing transpiration (per unit leaf area) thus improving what is termed 'water-use efficiency' (the ratio of crop biomass accumulation to the water used in evapotranspiration). A doubling of ambient CO_2 concentration causes about a 40% decrease in stomatal aperture in both C3 and C4 plants which may reduce transpiration by

23-46% (Morison, 1987; Cure and Acock, 1986). This might well help plants in environments where moisture currently limits growth, such as in semi-arid regions, but there remain many uncertainties, such as to what extent the greater leaf area of plants (resulting from increased CO_2) will balance the reduced transpiration per unit leaf area (Allen *et al.*, 1985; Gifford, 1988). In summary, we can expect that a doubling of atmospheric CO_2 concentrations from 330 to 660 ppmv might cause a 10-50% increase in growth and yield of C3 crops (such as wheat, rice and soybean) and a 0-10% increase for C4 crops (such as maize and sugar-cane) (Warrick *et al.*, 1987). Much depends, however, on the prevailing growing conditions. Our present knowledge is based on experiments mainly in field chambers and has not yet included extensive study of response in the field under suboptimal conditions. Thus, although there are indications that, overall, the effects of increased CO_2 could be distinctly beneficial and could partly compensate for some of the negative effects of CO_2-induced changes of climate, we cannot at present be sure that this will be so.

Effects of changes of climate

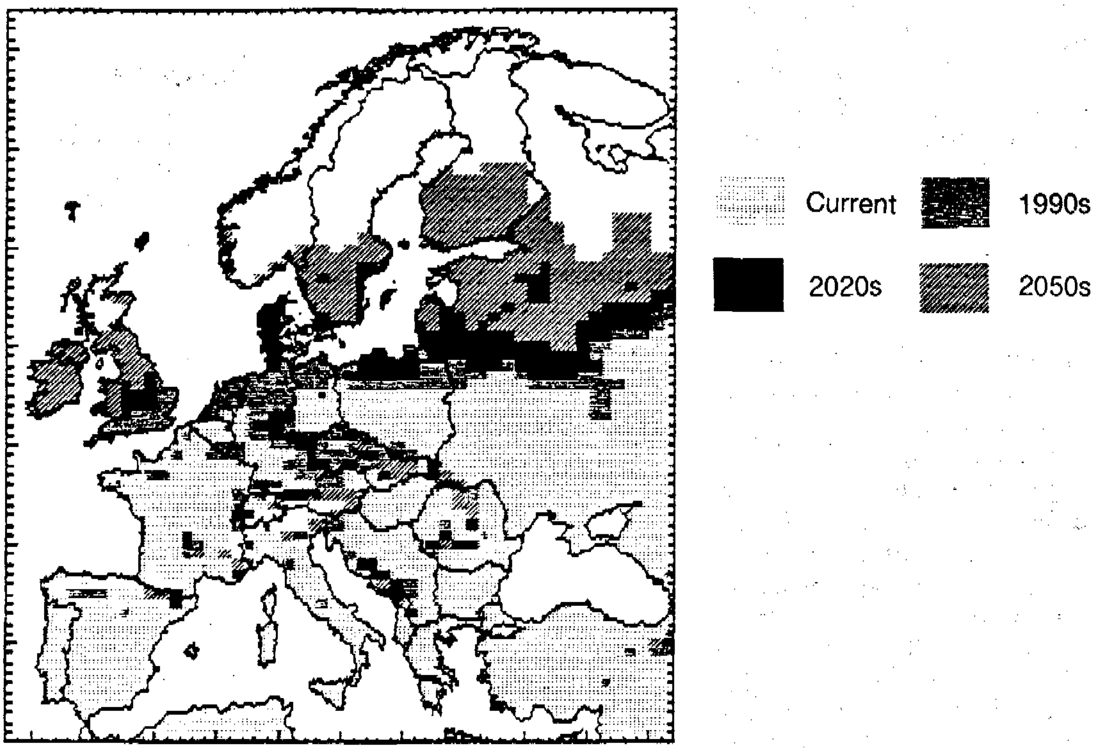
- Changes in thermal limits to agriculture

Increases in temperature can be expected to lengthen the growing season in areas where agricultural potential is currently limited by insufficient warmth, resulting in a poleward shift of thermal limits of agriculture. The consequent extension of potential will be most pronounced in the northern hemisphere because of the greater extent here of temperate agriculture at higher latitudes. There may, however, be important regional variations in our ability to exploit this shift. For example, the greater potential for exploitation of northern soils in Siberia than on the Canadian Shield may mean relatively greater increases in potential in northern Asia than in northern N America (Parry, 1990). A number of estimations have been made concerning the northward shift in productive potential in mid-latitude northern hemisphere countries (see, for example, Figure 2). These relate to changes in the climatic limits for specific crops under a variety of climatic scenarios, and are therefore not readily compatible (Newman, 1980; Blasing and Solomon, 1983; Rosenzweig, 1985; Williams and Oakes, 1978; Parry and Carter, 1988; Parry *et al.*, 1989). They suggest, however, that a 1°C increase in mean annual temperature would tend to advance the thermal limit of cereal cropping in the mid-latitude northern hemisphere by about 150-200 km, and to raise the altitudinal limit to arable agriculture by about 150-200 m. While warming may extend the margin of potential cropping and grazing in mid-latitude regions, it may reduce yield potential in the core areas of current production, because higher temperatures encourage more rapid maturation of plants and shorten the period of grain filling (Parry and Duinker, 1990). An important additional effect, especially in temperate mid-latitudes, is likely to be the reduction of winter chilling (vernalization). Many temperate crops require a period of low temperatures in winter either to initiate or accelerate the flowering process. Low vernalization results in low flower bud initiation and, ultimately, reduced yields. A 1°C warming has been estimated to reduce effective winter chilling by between 10 and 30%, thus contributing to a poleward shift of temperate crops (Salinger, 1989). Increases in temperature are also likely to affect the crop calendar in low latitude regions, particularly where more than one crop is harvested each year. For example, in Sri Lanka and Thailand, a 1°C warming would probably require a substantial re-arrangement of the current crop calendar which is finely tuned to present climatic conditions (Kaida and Surarerks, 1984; Yoshino, 1984).

- Shifts of moisture limits to agriculture

There is much less agreement between GCM-based projections concerning GHG-induced changes in precipitation than there is about temperature - not only concerning changes of magnitude, but also of spatial pattern and distribution through the year. For this reason it is difficult to identify potential shifts in the moisture limits to agriculture. This is particularly so because relatively small changes in the seasonal distribution of rainfall can have disproportionately large effects on the viability of agriculture in tropical areas, largely through changes in growing period when moisture is sufficient and thus through the timing of critical episodes such as planting, etc. However, recent surveys for the IPCC have made a preliminary identification of those regions where there is some agreement amongst 2 x CO_2 experiments with general circulation models concerning an overall reduction in crop-water availability (Parry, 1990; Parry

FIGURE 2
Grain maize limit under the GISS transient response Scenario in the 1990s, 2020s, and 2050s (relative to the limit for the current climate)



Source: Carter, *et al.*,1990

and Duinker, 1990). It should be emphasized that coincidence of results for these regions is not statistically significant. The regions are:

- Decreases of soil water in December, January and February:

Africa	:	north-east Africa, southern Africa
Asia	:	western Arabian Peninsula; SE Asia
Australasia	:	eastern Australia
N America	:	southern USA
S America	:	Argentine Pampas

- Decreases in soil water in June, July and August:

Africa	:	north Africa; west Africa
Europe	:	parts of western Europe
Asia	:	north and central China; parts of Soviet central Asia and Siberia
N America	:	southern USA and Central America
S America	:	eastern Brazil
Australasia	:	western Australia

- Regions affected by drought, heat stress and other extremes

Probably most important for agriculture, but about which least is known, are the possible changes in climatic extremes, such as the magnitude and frequency of drought, storms, heat waves and severe frosts (Rind *et al.*, 1989). Some modelling evidence suggests that hurricane intensities will increase with climatic warming (Emanuel, 1987). This has important implications for agriculture in low latitudes, particularly in coastal regions.

Since crop yields often exhibit a nonlinear response to heat or cold stress, changes in the probability of extreme temperature events can be significant (Mearns *et al.*, 1984; Parry, 1976). In addition, even assuming no change in the standard deviation of temperature maxima and minima, we should note that the frequency of hot and cold days can be markedly altered by changes in mean monthly temperature. To illustrate, under a 2 x CO_2 equilibrium climate, the number of days in which temperatures would fall below freezing would decrease from a current average of 39 to 20 in Atlanta, Georgia (USA), while the number of days above 90°F would increase from 17 to 53 (EPA, 1989). The frequency and extent of area over which losses of agricultural output could result from heat stress, particularly in tropical regions, is therefore likely to increase significantly. Unfortunately, no studies have yet been made of this. However, the apparently small increases in mean annual temperatures in tropical regions (*c.* 1-2°C under a 2 x CO_2 climate) could sufficiently increase heat stress on temperate crops such as wheat so that these are no longer suited to such areas. Important wheat producing areas such as N India could be affected in this way (Parry and Duinker, 1990).

There is a distinct possibility that, as a result of high rates of evapotranspiration, some regions in the tropics and subtropics could be characterised by a higher frequency of drought or a similar frequency of more intense drought than at present. Current uncertainties about how regional patterns of rainfall will alter mean that no useful prediction of this can at present be made. However, it is clear in some regions that relatively small decreases in water availability can readily produce drought conditions. In India, for example, lower-than-average rainfall in 1987 reduced food grains production from 152 to 134 million tonnes, lowering food buffer stocks from 23 to 9 million tonnes. Changes in the risk and intensity of drought, especially in currently drought-prone regions, represent potentially the most serious impact of climatic change on agriculture both at the global and the regional level.

- Effects on the distribution of agricultural pests and diseases

Studies suggest that temperature increases may extend the geographic range of some insect pests currently limited by temperature (EPA, 1989; Hill and Dimmmock, 1989). As with crops, such effects would probably be greatest at higher latitudes. The number of generations per year produced by multivoltine (i.e. multigenerational) pests would increase, with earlier establishment of pest populations in the growing season and increased abundance during more susceptible stages of growth. An important unknown, however, is the effect that changes in precipitation amount and air humidity may have on the insect pests themselves and on their predators, parasites and diseases. Climate change may significantly influence interspecific interactions between pests and their predators and parasites. Under a warmer climate at mid-latitudes there would be an increase in the overwintering range and population density of a number of important agricultural pests, such as the potato leafhopper which is a serious pest of soybeans and other crops in the USA (EPA, 1989). Assuming planting dates did not change, warmer temperatures would lead to invasions earlier in the growing season and probably lead to greater damage to crops. In the US Corn Belt increased damage to soybeans is also expected due to earlier infestation by the corn earworm.

Examination of the effect of climatic warming on the distribution of livestock diseases suggests that those at present limited to tropical countries, such as Rift Valley fever and African Swine fever, may spread into the mid-latitudes. For example, the horn fly, which currently causes losses of $ 730.3 million in the US beef and dairy cattle industries might extend its range under a warmer climate leading to reduced gain in beef cattle and a significant reduction in milk production (Drummond, 1987; EPA, 1989). In cool temperate regions, where insect pests and diseases are not generally serious at present, damage is likely to increase under warmer conditions. In Iceland, for example, potato blight currently does little damage to potato crops, being limited by the low summer temperatures. However, under a 2 x CO_2 climate that may be 4°C warmer than at present, crop losses to disease may increase to 15% (Bergthorsson *et al.*, 1988). Most agricultural diseases have greater potential to reach severe levels under warmer and more humid conditions (Beresford and Fullerton, 1989). Under warmer and more humid conditions cereals would be more prone to diseases such as Septoria. In addition, increases in population levels of disease vectors may well lead to increased epidemics of the diseases they carry. To illustrate, increases in infestations of the Bird Cherry aphid (*Rhopalosiphum padi*) or

Grain aphid (*Sitobian avenae*) could lead to increased incidence of Barley Yellow Dwarf Virus in cereals.

Effects of sea-level rise on agriculture

Greenhouse gas-induced warming is expected to lead to rises in sea level as a result of thermal expansion of the oceans and partial melting of glaciers and ice caps, and this in turn is expected to affect agriculture, mainly through the inundation of low-lying farmland but also through the increased salinity of coastal groundwater. The current projection of sea-level rise above present levels is 20±10 cm by *c.* 2030, and 30±15 cm by 2050 (Warrick and Oerlemans, 1990).

Preliminary surveys of proneness to inundation have been based on a study of existing contoured topographic maps, in conjunction with knowledge of the local 'wave climate' that varies between different coastlines. They have identified 27 countries as being especially vulnerable to sea-level rise, on the basis of the extent of land liable to inundation, the population at risk and the capability to take protective measures (UNEP, 1989). It should be emphasised, however, that these surveys assume a much larger rise in sea levels than is at present estimated to occur within the next century under current trends of increase of GHG concentrations. On an ascending scale of vulnerability (1 to 10) experts identified the following most vulnerable countries or regions: 10, Bangladesh; 9, Egypt, Thailand; 8, China; 7, western Denmark; 6, Louisiana; 4, Indonesia. The most severe impacts are likely to stem directly from inundation. South East Asia would be most affected because of the extreme vulnerability of several large and heavily populated deltaic regions. For example, with a 1.5 m sea-level rise, about 15% of all land (and about one-fifth of all farmland) in Bangladesh would be inundated and a further 6% would become more prone to frequent flooding (UNEP, 1989). Altogether 21% of agricultural production could be lost. In Egypt, it is estimated that 17% of national agricultural production and 20% of all farmland, especially the most productive farmland, would be lost as a result of a 1.5 m sea-level rise. Island nations, particularly low-lying coral atolls, have the most to lose. The Maldive Islands in the Indian Ocean would have one-half of their land area inundated with a 2 m rise in sea level (UNEP, 1989).

In addition to direct farmland loss from inundation, it is likely that agriculture would experience increased costs from saltwater intrusion into surface water and groundwater in coastal regions. Deeper tidal penetration would increase the risk of flooding and rates of abstraction of groundwater might need to be reduced to prevent re-charge of aquifers with sea water. Further indirect impacts would be likely as a result of the need to relocate both farming populations and production in other regions. In Bangladesh, for example, about one-fifth of the nation's population would be displaced as a result of the farmland loss estimated for a 1.5 m sea-level rise. It is important to emphasize, however, that the IPCC estimates of sea-level rise are much lower than this (about 0.5 m by 2090 under the IPCC 'Business-As-Usual case').

Summary of plant, pest and sea-level effects

Potential impacts on yields vary greatly according to types of climate change and types of agriculture. In general, there is much uncertainty about how agricultural potential may be affected. In the northern mid-latitudes where summer drying may reduce productive potential (e.g. in the US Great Plains and Corn Belt, Canadian Prairies, southern Europe, south European former USSR) yield potential is estimated to fall by *c.* 10-30% under an equilibrium 2 x CO_2 climate (Parry, 1990). However, towards the northern edge of current core-producing regions (e.g. the northern edge of the Canadian Prairies, northern Europe, northern states of the former Soviet Union and Japan, southern Chile and Argentina) warming may enhance productive potential, particularly when combined with beneficial direct CO_2 effects. Much of this potential may not, however, be exploitable owing to limits placed by inappropriate soils and difficult terrain, and on balance it seems that the advantages of warming at higher latitudes would not compensate for reduced potential in current major cereal producing regions.

Effects at lower latitudes are much more difficult to estimate because production potential is largely a function of the amount and distribution of precipitation and because there is little agreement about how precipitation may be affected by GHG warming. Because of these uncertainties the tendency has been to assert that worthwhile study must await improved projection of changes in precipitation. Consequently very few estimates are currently available of how yields might respond to a range of possible changes of climate in low-latitude regions. The only comprehensive national estimates available are for Australia where increases in cereal and grassland productivity might occur (except in western Australia) if warming is accompanied by increase in summer rainfall (Pearman, 1988).

The impacts described above relate to possible changes in potential productivity or yield. It should be emphasised that such potential effects are those estimated assuming present-day management and technology. They are not the estimated future actual effects, which will depend on how farmers and governments respond to altered potential through changes in management and technology. The likely effects on actual agricultural output and on other measures of economic performance such as profitability and employment levels are considered in the next section.

EFFECTS ON PRODUCTION AND LAND USE

To date (1992) six national case studies have been made of the potential impact of climatic changes on agricultural production (in Canada, Iceland, Finland, the former Soviet Union, Japan and the United States) (Parry *et al.*, 1989; Smit, 1989; EPA, 1989). These studies are based on results from model experiments of yield responses to altered climate and the effects that altered yields might have on production. Other countries have conducted national reviews of effects of climate change, basing these on existing knowledge rather than on new research. The most comprehensive of these are for Australia and New Zealand (Pearman, 1988; Salinger *et al.*, 1990). Brief surveys have also been completed in the UK and West Germany (SCEGB, 1989). Several other national assessments are currently in progress but not yet complete. This section provides a summary of results from the most detailed of these surveys. These provide us with an array of assessments for three world regions: the northern and southern mid-latitude grain belts and northern regions at the current margin of the grain belt. We shall take these regions in turn. Unless otherwise stated the estimated effects are for climates described by 2 x CO_2 GCM experiments. No national assessments have been completed using climates described by transient response GCM experiments. Some of the estimates relate to the effect only of altered climate, others the combined effect of altered climate and the direct effect of increased atmospheric CO_2.

Effects on production in the northern and southern mid-latitude grain belts

- United States

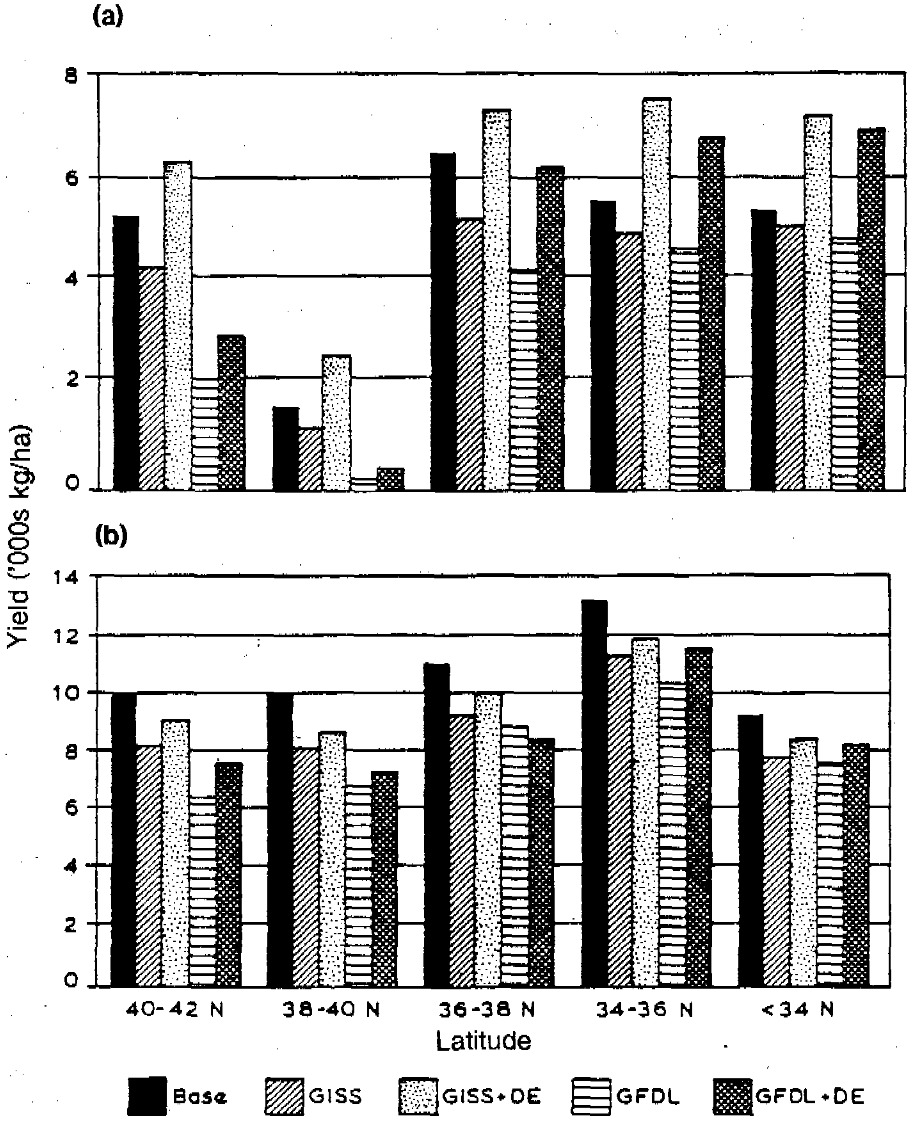
Increased temperatures and reduced crop water availability projected under the GISS and GDFL 2 x CO_2 climate experiments are estimated to lead to a decrease of yields of all the major unirrigated crops (EPA, 1989) (Figure 3). The largest reductions are projected for the south and south-east. In the most northern areas, however, where temperature is currently a constraint on growth, yields of unirrigated maize and soybeans could increase as higher temperatures increase the length of the available growing season. When the direct effects of increased CO_2 are considered, it is evident that yields may increase more generally in northern areas but still decrease in the south where problems of heat stress would increase and where rainfall may decrease. Production of most crops is estimated to be reduced because of yield decreases and limited availability of suitable land. The largest reductions are in sorghum (-20%), corn (-13%) and rice (-11%), with an estimated fall in net value of agricultural output of $ 33 billion. If this occurred, consumers would face slightly higher prices, although supplies are estimated to meet current and projected demand. However, exports of agricultural commodities could decline by up to 70%, and this could have a substantial effect on the pattern of world food trade.

- Canada

On the Canadian prairies, where growing season temperatures under the GISS 2 x CO_2 equilibrium climate would be about 3.5°C higher than today, average potential yields could

FIGURE 3

Estimated maize yields in the USA under the GISS and GFDL 2 x CO_2 with and without the direct effects (DE) of CO_2 (a) dryland and (b) irrigated



Notes: Estimations for direct effects assume CO_2 concentrations of 660 ppm which are 100 ppm above IPCC estimates and are thus somewhat exaggerated
Source: Rosenzweig, 1989

decrease 10 to 30%. Spring wheat yields in Saskatchewan are estimated to fall by 28% (Williams *et al.*, 1988). Since Saskatchewan at present produces 18% of all the world's traded wheat, such a reduction could well have global implications. Assuming (unrealistically) that the present-day relationship between production and profit in Saskatchewan holds in the future, average farm household income is estimated to fall by 12%, resulting in a reduction in expenditure by agriculture of Can$ 277 million on the goods and services provided by other sectors, leading to a Can$ 250 million (6%) reduction in provincial GDP in sectors other than agriculture and a 1% loss of jobs. In Ontario, precipitation increases of up to 50% would be more than offset by increases in evapotranspiration with consequent increased moisture stress on crops (Smit, 1987). Maize and soybean would thus become very risky in the southern part of the province. In the north, where maize and soybean cannot currently be grown commercially because of inadequate warmth, cultivation may become profitable but this is not expected to compensate for reduced potential further south and, if there were no adjustment of current land use and farming systems, the overall cost in lost production is reckoned at Can$ 100 million to 170 million.

- Japan

Under a warming of 3.0-3.5°C and a 5% increase in annual precipitation (the GISS 2 x CO_2 climate), rice yields are expected to increase in the north (Hokkaido) by *c.* 5%, and in the north-central region (Tohoku) by *c.* 2%, if appropriate technological adjustments are made (Yoshino *et al.*, 1988). The average increase for the country overall is *c.* 2-5%. Cultivation limits for rice would rise about 500 m and advance *c.* 100 km north in Hokkaido. Yields of maize and soybeans are both estimated to increase by about 4%. Sugar-cane yields in the most southern part of Japan could decrease if rainfall was reduced. The northern economic limit of citrus fruits would shift from southern Japan to northern Honshu Island (Yoshino, personal communication, 1989). Net primary productivity of natural vegetation is expected to increase by *c.* 15% in the north, *c.* 7% in the centre and south of Japan (Yoshino *et al.*, 1988).

- Australia and New Zealand

In Australia and New Zealand national assessments have been based on a thorough review of existing knowledge and on use of expert judgement rather than on model experiments (Pearman, 1988; Salinger *et al.*, 1990). Overall, it is reckoned that wheat production in Australia could increase under a 2 x CO_2 climate, assuming a quite simple scenario of increased summer rainfall, decreased winter rainfall and a general warming of 3°C. Increases are expected in all states except Western Australia, where more aridity might cause a significant reduction in output (Pittock, 1989). More generally, the major impact of production would probably be on the drier frontiers of arable cropping. For example, increases in rainfall in subtropical northern Australia could result in increased sorghum production at the expense of wheat. Increased heat stress might shift livestock farming and wool production southward with sheep possibly replacing arable farming in some southern regions. Many areas currently under fruit production would no longer be suitable under a 3°C warming, and would need to shift southwards or to higher elevations in order to maintain present levels of production. All of these changes would also be affected by changes in the distribution of diseases and pests.

Effects on production in northern marginal regions

Some of the most pronounced effects on agriculture would be likely to occur in high-latitude regions because GHG-induced warming is projected to be greatest here and because this warming could remove current thermal constraints on farming. Inappropriate terrain and soils are, however, likely to limit the increase in extent of the farmed area and, in global terms, production increases would probably be small (Parry, 1990). A summary of available information is given below.

- Iceland

With mean annual temperatures increased by 4.0°C and precipitation 15% above the present average (consistent with the GISS 2 x CO_2 climate), the onset of the growing season of grass in Iceland would be brought forward by almost 50 days, hay yields on improved pastures would increase by about two-thirds and herbage on unimproved rangelands by about a half (Bergthorsson *et al.*, 1988). The numbers of sheep that could be carried on the pastures would be raised by about 250% and on the rangelands by two-thirds if the average carcass weight of sheep and lambs is maintained as at present. At a guess, output of Icelandic agriculture could probably double with a warming of 4°C.

- Finland

Assuming in Finland an increase in summer warmth by about a third and precipitation by about half (consistent with the GISS 2 x CO_2 climate) barley and spring wheat yields increase about 10% in the south of the country but slightly more in the north (due to relatively greater warming and lower present-day yields) (Kettunen *et al.*, 1988). The area under grain production in

Finland might increase at the expense of grass and livestock production as a consequence of raised profitability, with the greatest extension being in winter crops such as wheat rather than spring crops such as barley or oats.

- Northern states former Soviet Union

The only other region for which an integrated impact assessment has been completed is in north European former Soviet Union. In the Leningrad and Cherdyn regions, under climates that are 2.2-2.7°C warmer during the growing season and 36-50% wetter (consistent with the GISS 2 x CO_2 climate), winter rye yields are estimated to decrease by about a quarter due to faster growth and increased heat stress under the higher temperatures (Pitovranov *et al.*, 1988a and b). However, crops such as winter wheat and maize, which are currently low yielding because of the relatively short growing season in these regions, are better able to exploit the higher temperatures and exhibit yield increases in Cherdyn of up to 28% and 6% respectively with a 1°C warming.

The differential yield responses described above are reflected in substantial changes in production costs incurred in meeting production targets. Thus, while production costs for winter wheat and maize in the Central Region around Moscow are estimated to be reduced by 22% and 6% under a 1°C warming and with no change in precipitation, they increase for most other crops, particularly quick-maturing spring-sown ones which are the dominant crops today. This would suggest that quite major switches of land use would result and the land allocation models used in the study indicate that, to optimise land use by minimising production costs, winter wheat and maize would extend their area by 29% and 5% while barley, oats and potatoes would decrease in extent.

- Summary of potential effects in mid-latitude regions

The effects of possible climatic changes on regional and national production have not yet been investigated in any great detail, nor for more than a few case studies. The effects are strongly dependent on the many adjustments in agricultural technology and management that undoubtedly will occur in response to any climatic change. So numerous and varied are these potential adjustments that it is extraordinarily difficult to evaluate their ultimate effect on aggregate production. In this section we have therefore considered the effects on production that are likely to stem directly from changes in yield, unmodified by altered technology and management. Adjustments in technology will be considered, briefly, in the last section of this paper. In summary, it seems that overall output from the major present-day grain producing regions could well decrease under the warming and possible drying expected in these regions. In the USA grain production may be reduced by 10-20% and, while production would still be sufficient for domestic needs, the amount for export would probably decline. Production may also decrease in the Canadian prairies and in the southern former Soviet Union. In Europe production of grains might increase in the UK and the Low Countries if rainfall increases sufficiently, but may fall in southern Europe substantially if there are significant decreases in rainfall as currently estimated in most GCM 2 x CO_2 experiments (Parry, 1990). Output could increase in Australia if there is a sufficient increase in summer rainfall to compensate for higher temperatures. Production could increase in regions currently near the low-temperature limit of grain growing: in the northern hemisphere in the northern Prairies, Scandinavia, north European (former) Soviet Union; and in the southern hemisphere in southern New Zealand, and southern parts of Argentina and Chile. But it is reasonably clear that, because of the limited area unconstrained by inappropriate soils and terrain, increased high-latitude output will probably not compensate for reduced output at mid-latitudes. The implications of this for global food supply and food security are considered in the next section.

IMPLICATIONS FOR GLOBAL FOOD SECURITY

Although, on average, global food supply currently exceeds demand by about 10-20, its year-to-year variation (which is about ±10%) can reduce supply in certain years to levels where it is barely sufficient to meet requirements. In addition, there are major regional variations in the balance between supply and demand, with perhaps a billion people (about 15% of the world's population) not having secure access to sufficient quantity or quality of food to lead fully productive lives. For this reason the working group on food security at the 1988 Toronto Conference on 'The Changing Atmosphere' concluded that:

> "While averaged global food supplies may not be seriously threatened, unless appropriate action is taken to anticipate climate change and adapt to it, serious regional and year-to-year food shortages may result, with particular impact on vulnerable groups".

Statements such as this are, however, based more on intuition than on knowledge derived from specific study of the possible impact of climate change on the food supply. No such study has yet been completed, although one is currently being conducted by the US Environmental Protection Agency and is due to report in 1992. The information available at present is extremely limited. It has for example, been estimated that increased costs of food production due to climate change could reduce per caput global GNP by a few percentage points (Schelling, 1983). Others have argued that technological changes in agriculture will override any negative effects of climate changes and, at the global level, there is no compelling evidence that food supplies will be radically diminished (Crosson, 1989). Recent reviews have tended to conclude however that, at a regional level, food security could be seriously threatened by climate change, particularly in less developed countries in the semi-arid and humid tropics (Parry, 1990; Parry and Duinker, 1990). Analyses conducted for the IPCC, designed to test the sensitivity of the world food system to changes of climate, indicate what magnitudes and rates of climatic change could possibly be absorbed without severe impact and, alternatively, what magnitudes and rates could seriously perturb the system (Parry, 1990; Parry and Duinker, 1990). These suggest that yield reductions of up to 20% in the major mid-latitude grain exporting regions could be tolerated without a major interruption of global food supplies. However, the increase in food prices (7% under a 10% yield reduction) could seriously influence the ability of food-deficit countries to pay for food imports, eroding the amount of foreign currency available for promoting development of their non-agricultural sectors. It should be emphasized that these analyses are preliminary and more work is necessary before we have an adequate picture of the resilience of the world food system to climatic change.

CONCLUSIONS

Our assessment of possible effects has, up to this point, assumed that technology and management in agriculture do not alter significantly in response to climatic change, and thus do not alter the magnitude and nature of the impacts that may stem from that change. It is certain, however, that agriculture will adjust and, although these adjustments will be constrained by economic and political factors, it is likely that they will have an important bearing on future impacts. On balance, the evidence is that food production at the global level can, in the face of estimated changes of climate, be sustained at levels that would occur without a change of climate, but the cost of achieving this is unclear. It could be very large. Increases in productive potential at high mid-latitudes and high latitudes, while being of regional importance, are not likely to open up large new areas for production. The gains in productive potential here due to climatic warming would be unlikely to balance possible large-scale reductions in potential in some major grain-exporting regions at mid-latitude. Moreover, there may well occur severe negative impacts of climate change on food supply at the regional level, particularly in regions of high present-day vulnerability least able to adjust technically to such effects. The average global increase in overall production costs could thus be small (perhaps a few percent of world agricultural GDP). Much depends however, on how beneficial are the so-called 'direct' effects of increased CO_2 on crop yield. If plant productivity is substantially enhanced *and* more moisture is available in some major production areas, then world productive potential of staple cereals could increase relative to demand with food prices reduced as a result. If, on the contrary, there is little beneficial direct CO_2 effect *and* climate changes are negative for world agricultural production could increase significantly, these increased costs amounting to perhaps over 10% of world agricultural GDP.

Although we know little, at present, about how the frequency of extreme weather events may alter as a result of climatic change, the potential impact of concurrent drought or heat stress in the major food-exporting regions of the world could be severe. In addition, relatively small decreases in rainfall or increases in evapotranspiration could markedly increase both the risk and the intensity of drought in currently drought-prone (and often food-deficient) regions. Change in drought-risk represents potentially the most serious impact of climatic change on agriculture both at the regional and the global level. The regions most at risk from impact from climatic change are probably those currently most vulnerable to climatic variability. Frequently these are low-income regions with a limited ability to adapt through technological change. This paper has emphasised the inadequacy of our present knowledge. It is clear that more information on potential impacts would help us identify the full range of potentially useful responses and assist in determining which of these may be most valuable.

Some priorities for future research may be summarised as follows:

- Improved knowledge is needed of effects of changes in climate on crop yields and livestock productivity in different regions and under varying types of management; on soil-nutrient depletion; on hydrological conditions as they effect irrigation-water availability; on pests, diseases and soil microbes, and their vectors; and on rates of soil erosion and salinisation.

- Further information is needed on the range of potentially effective technical adjustments at the farm and village level (e.g. irrigation, crop selection, fertilizing, etc.); on the economic, environmental and political constraints on such adjustments; and on the range of potentially effective policy responses at regional, national and international levels (e.g. re-allocations of land use, plant breeding, improved agricultural extension schemes, large-scale water transfers).

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DISCUSSION

The discussion opened with a question on comparison between the level of climatic change predicted and annual variation as well as recent changes in the Sahel. In response the author said that 1976 was a 1 in 800-year event in the UK but with the predicted change it would be a 1 in 20 event. The 200-300 km southward move of the desert in the Sahel in the 1960s and 1970s is the degree of change predicted for a 1°C rise in temperature. No generalisations about changes in climatic variability are possible. It was also agreed that the regional estimates are not yet reliable enough and that standard errors should be added to the estimates. In about 10 years it is expected that sufficiently good models will have been developed to be reasonably sure of the signs of climatic change. It was suggested that climatic change might be an opportunity in that better farmers might respond to the change with output that replaced that of less efficient farmers. It was said that the issue is one of reducing vulnerability and increasing resilience in agricultural systems.