Economic Aspects and Policy Issues in Groundwater Development

World Bank Staff Working Paper No. 496

SWP496

October 1981

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THE WORLD BANK

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ECONOMIC ASPECTS AND POLICY ISSUES IN GROUNDWATER DEVELOPMENT

Technical, economic and social aspects of groundwater development policy are discussed. The various groundwater system components and categories of agricultural demands are analysed. Opportunities exist for obtaining benefits from conjunctive use with surface water. These are stressed as well as the economic aspects of wells and well-field design and the need to consider drainage before soil problems become insurmountable. Groundwater development is usually very profitable, and it is therefore likely to be monopolised by a few farmers or overexploited by the majority. Public control to obtain an equitable regime is desirable, but institutional barriers are enormous. The pros and cons of public and private sector development are discussed. Once they are developed, aquifers need overall management to maximise economic yield and to safeguard water quality. Operating experiences from several countries are quoted, and the role of mathematical models to gain improved insight is briefly considered. An analytical framework for research into key topics is presented.

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Preface

This study examines a wide range of economic and policy issues related to development of groundwater for irrigation. Its purpose is twofold. First, it is one of the background papers expected to be used in preparation of a Bank policy paper on irrigation. In this context it was designed to provide an overview of the opportunities and constraints in development of these resources and to complement several other papers dealing with institutional aspects of water distribution and management of irrigation systems. Second, the study was oriented towards eventually providing operational guidelines for country irrigation sub-sector work and project identification and preparation. As a step in this direction the paper was reviewed with Bank staff in July 1981 to identify priority areas for further in-depth study to provide insights on critical planning and operational issues. As a result of this review it is planned that further study will address questions such as : conjunctive use of ground and surface water; the role of public and private enterprise in ownership of wells; operation and maintenance and aquifer management under long run sustained yield and mining situations.

SUMMARY

The paper presents a review of policy issues which are relevant to groundwater exploitation in the developing countries of the world. It examines the economic, technical and social issues which arise in the use of groundwater for irrigation and domestic water supplies and also those involved in the conjunctive use of ground and surface waters. The aim is to direct attention to crucial areas and to produce hypotheses which will be subsequently tested and verified so as to enable guidelines to be prepared for use in the evaluation of future projects.

System Characteristics

In discussing the characteristics of groundwater systems, a wide view is taken of the components comprising such systems, stretching from the nature of aquifers to the ultimate uses of groundwater. Distinction is made between the resources underlying the vast alluvial plains, such as the Indo-Gangetic plain, those contained in deep rock aquifers, whether fissured or granular, and those in the upper weathered zone.

Exploitation of the resources by hand pumped wells, shallow and deep tubewells is presented with special reference to Bangladesh where all these methods are in use. Problems are discussed in regard to control of the use of the resources by these various methods and the possible difficulties with mutual interference between deep and shallow wells.

Demand patterns are treated in some detail, especially in regard to irrigation - which is, by far, the largest user of the resources. Groundwater can be operated in the same way as a surface storage reservoir to supply water during critical periods of the year, thus making more economic use of surface sources. As a corollary to this argument, the value of groundwater as an insurance is pointed out in terms of supplementing inadequate rainfall and in compensating for the often substandard working of canal irrigation networks.

Development of groundwater as a substitute for surface water schemes is mentioned and the advantages of much reduced capital costs and much shorter lead times emphasised. Further advantages are that smaller packets of land and areas with more difficult topography can be irrigated.

Wells and Wellfields

As a preface to the discussion on the economics of wells and wellfields, a section is included on the various drilling techniques ranging from cheap simple hand operated methods to the most sophisticated modern rotary drilling. The merits of well casings and screens of differing designs are discussed - also, the types of pumps usually employed. Reference is made to the corrosive nature of groundwater and the need to pay attention to this factor in selecting materials.

A method of optimising the design of wells in alluvium is outlined which minimises the present value of capital and operating costs. It illustrates that there is an optimum depth for wells in a deep uniform aquifer and also points

out that well diameters and discharges can be optimised in a similar manner. Substantial cost savings can also be made by optimising the wellfield as a whole. This takes into account well spacing and regional drawdown. In most cases a model is necessary for this latter purpose.

Drainage

The upper groundwater - that near the ground surface - is often treated as though it were a separate body, whereas in the great alluvial plains it is essentially part of a continuous system. It is this upper groundwater which is involved in drainage and, in some cases, it is cheaper and more effective to reduce the watertable level using wells rather than to use conventional methods. If the pumped water can be used for irrigation, then drainage objectives can be met at virtually no cost. Regretably drainage is still very much the 'poor relation' in the vast irrigated areas of developing countries. Traditionally politicians have seen votes in irrigation, but none in drainage and, in the battle for adequate operation and maintenance funds, it is usually drainage which suffers. Even at the planning report stage the case for irrigation is much more easily made than that for drainage. This is partly due to the fact that the response of crops to various degrees of drainage is not yet known with any precision and, in fact, the complex relationship between soil texture, soil and water chemistry, depth to watertable and tolerance of various crops to adverse conditions may present too many variables to researchers for any practical ground rules to be developed. And yet there are many thousands of hectares of agricultural land being lost every year due to inadequate or non-existent drainage.

Once an irrigation system has been established, the subsequent cost of drainage is huge. Outfall drains alone, as found in the Left Bank Outfall Drain in Pakistan, can absorb virtually all of the development funds but, even then, such expenditure is the lesser part when compared with the vast minor drainage reticulation necessary. For future projects, the trend will have to be towards installing drainage together with the irrigation system.

Equitable Distribution

There is still great potential for further groundwater development, even though some very large projects have been implemented and extensive private developments have taken place. In India, for example, probably only about 30% of the resource is being used. By contrast, there are areas where over-exploitation has taken place, resulting in falling watertables, wells drying up and permanent aquifer damage.

There is little doubt that the development of groundwater is usually a vastly profitable exercise and, as such, it is likely to be monopolised by the few - or over-exploited by the many. In either case, there must be a degree of public control if equitable distribution is an objective and if the exploitation is to be managed and planned.

This principle is simply stated and virtually incontrovertable but, in practice, the difficulties are enormous. The legal framework is often inadequate and, in that, traditionally private rights are involved - which would be infringed by attempts at public control; it may be difficult to change the situation. Conceptually there are even problems with regard to the notion of equitable distribution if groundwater is to be regarded as a common property resource. Does equitable distribution mean a share of the water for everyone, or does it mean a share of the benefits arising from the most efficient use of the resource? These problems are partly political and partly economic, but projects are sometimes used to advocate purely political objectives. Income redistribution is one of these. Such objectives have a poor record of success and too often neglect, in absolute terms, the increase which can be achieved in the poverty group - even though income disparities may widen.

Efforts to control development with limits on minimum spacing of wells, control of power connections, credit control and so on all tend to preserve the interests of those who have established prior rights - the rich, the literate and the influential - and thus conspire to conserve existing income distribution patterns. In other words, the rich get richer.

At the very least, the law should provide for registration of all abstractions from groundwater but, ultimately, much more than that if over-exploitation is to be avoided. There is generally a need for an adequate national groundwater law. For example, individual states in the USA are responsbile for their own body of law and a number of interesting frameworks are being developed; these frameworks could be used in developing countries where the problems are similar.

Public or Private

There is a long-running debate on whether groundwater should be developed in the private or in the public domain. There is inevitably much to be said in each cause - as is usual with such strongly polarised positions.

Public enterprise has had a distinct role in pioneering large scale groundwater projects and in extensive exploratory programmes to define the very nature of the resource. In this respect the public initiative has been an essential pre-requisite without which the private sector would have been unaware of the potential.

Insofar as any irrigation system is equitable, the large groundwater projects where wells discharge into established irrigation canals do ensure reasonable equity and, certainly, some of the benefits reach the poverty groups.

Technological progress in the groundwater field, in terms of planning and managing projects, is virtually limited to the public sector. Such problems as optimising the design of a system, investigating and testing new materials, modelling an aquifer, integrating with surface water supplies, operating the aquifer as a storage reservoir and controlling saline intrusion are all matters which can be undertaken by a public authority, but cannot be done in the private sector.

Private development, on the other hand, can score on several accounts. It can mobilise capital, which might otherwise lie dormant, and progress is generally far more rapid than in the public sector.

The overwhelming advantage of private ownership of wells is in the matter of maintenance and control of the water. At the individual well level, the private operator is much more efficient.

Private farmers generally elect for low technology. Their aims are short term and they therefore employ cheap materials. Risks are high and there are frequent failures, but the private individual is prepared to take these risks whereas a public authority dare not entertain a possible high failure rate. Thus we find high technology strenuously defended on economic grounds in the public domain and the low technology of the private sector equally strongly defended by the appropriate technology faction.

Uncontrolled private development, even with low technology, can lead to excessive investment per unit of area. In the effort for each farmer to own his own well, there are cases of ten or more wells in one area which could reasonably be irrigated by one.

The paradox is thus that private developers are able to install and operate a well efficiently but cannot possibly begin to consider overall management, either of the total investment or even of the resource itself, particularly if this involves the use of saline water or integrating with surface sources. It seems therefore that some form of overall government control would provide the best compromise, with farmer groups operating and maintaining the wells.

Development Choices

In those areas already mentioned where government is clearly the only body concerned, there are a number of options open. Conjunctive use with surface water is one such option. This can be achieved by using groundwater to supply an existing demand and diverting surface water elsewhere either to supplement inadequate surface supplies in time of shortage, to bolster an inadequate or erratic rainfall, to extend an irrigation season (at either end) to enable more valuable crops to be grown, or to mix with surface supplies to provide extra water where the quality of groundwater is marginal. Groundwater can also be pumped extensively during the dry season provided that there is adequate recharge in the wet season. Many of these options are available but very few are operated, although there are enormous potential benefits involved.

Another area where savings may be made is in the joint operation of electricity and groundwater schemes. If wells are electrically operated, they provide a large load centre which can be operated to reduce peak demand. This reduces the installed generating capacity required but, for the same daily production at the wellfield, increases the capacity of the transmission and distribution lines, and also increases either the number of wells or the pump size required in each well. The problem is susceptible to analysis.

The continued neglect of maintenance by public authorities has been commented upon earlier. So much is this the case that some projects now need rehabilitating to restore their performance to an acceptable level. Clearly in the competition for scarce resources this is an alternative to investing in a new project. Unfortunately rehabilitation lacks glamour but economically the returns on the investment are very attractive.

Aquifer Management

So far the discussion on management has centred on the matter of handling the water produced rather than the management of aquifer itself. Generally the concept of 'balanced recharge' - that is, pumping only that quantity of water which will be replaced by recharge - is accepted, although this term has little meaning unless it is related to time. For example, there is no reason to limit pumping to that recharge which can be guaranteed each year. If there is no long term depletion, then the balanced recharge criterion is met, but there are also spatial factors involved in this concept. In any basin where rivers or canals are in direct contact with the aquifer, a general lowering of the watertable will increase the recharge from surface sources. If the groundwater is operated as a reservoir and some surface water is escaping to the sea, then it may be desirable to control the groundwater at a level to encourage as much recharge from surface water as possible.

Balanced recharge is not the only possibility and, in fact, has little relevance in some of the world's great aquifer systems where recharge is negligible. In such cases, the groundwater must be 'mined' if it is to be used at all. This is an emotive subject because water is so bound up with tradition, custom and even religion that it becomes difficult in many societies to look upon it as an exploitable resource to be mined like oil or minerals. Nevertheless, mining is carried out and, indeed, in some areas, there could be no economic activity without it.

Water should be treated as any other of the earth's resources; it must thus be used intelligently and a balance should be struck between immediate needs and those of succeeding generations.

Several examples of groundwater mining operations are quoted and the thesis is put forward that the economic activity produced can eventually provide sufficient capital to supplement or entirely substitute for the mined groundwater.

Water quality is another subject of endless debate and, while the standards set by the World Health Organisation for potable water are generally acceptable there is much room for questioning those generally adopted for irrigation. The importance of this matter in the groundwater context cannot be over-emphasised, because the potential resource is much larger if the poorer qualities can be used. Against this is the fact that a higher standard of management at farm level is necessary if more saline waters are to be used and, furthermore, there must be adequate drainage. However, given these conditions, examples are quoted where some very saline waters are being used either directly or after mixing with surface water.

Other quality problems discussed include sea water intrusion of coastal aquifers, contamination of groundwater by sewage or industrial waste and desalination of poor quality water for domestic supplies.

Aquifer management can scarcely be considered today without the idea of models being introduced. These may include simple hydraulic or analogue models but these have largely been overtaken by digital models which produce faster results, can be easily changed and can be used for very complicated geometry.

Two main kinds of model are used, sometimes in conjunction. The first is a resource model which may look at the overall demand and allocation of water resources in a basin, and the second involves an aquifer (or aquifer system) which models the behaviour of the groundwater reservoir under various imposed abstraction conditions. Models of either type are a most useful planning tool but few have been used to date in an active management capacity. However, this is a role that will be increasingly used in the coming years.

Aquifer models require large quantities of data and also some historical information which can be used for calibration purposes. The important thesis here is that, if the present position can be demonstrated by the model from historic data, then the future position can be predicted with some confidence. All too frequently the data base is inadequate and inaccurate but, because models are fashionable, they are still demanded.

The weakness of the resource allocation model - often based on linear programming techniques - is that it is completely unable to meet the condition of forecasting the present position from historic data. This is not to cast any doubt on the powerful analytical technique, nor on the value of the discipline involved, but merely to say that the understanding of the complexities of the real world is inadequate as yet to enable such models to be used as accurate predictive tools.

The Future

The paper concludes with an annex suggesting an analytical framework for further research and an agenda for topics of such research which is presented as a series of provocative statements under the headings - technical, economic, legal, political, financial, administrative and social.

1. INTRODUCTION

Fresh water is now widely recognised to be a valuable and, increasingly, a scarce resource. Groundwater resources are extensive, abstraction technology is tested but the requirements and possibilities for successful development are not widely known to government officials, planners and engineers.

There is more fresh water stored in the ground than in all the lakes and rivers in the world. Estimates vary but accessible fresh groundwater is about thirty times the stored surface water (UN 1975). Many communities are dependent upon it. In very arid areas 70 to 100% of all water already comes from groundwater (e.g. Saudi Arabia almost 100%, Tunisia 75 to 95%, Israel 70%). Even in the more humid USA, 20% of total water used is pumped from groundwater and almost one half of the population are dependent upon underground sources for drinking water (US Committee on Irrigation, Drainage and Flood Control ICID 1978). In the Mediterranean and temperate regions of Western Europe three-quarters of drinking water comes from underground.

Although the bulk of world groundwater resources are still unused, the technology for developing it and the opportunities for beneficial use have increased greatly in recent years. Groundwater technology has benefited considerably from spin-offs of fossil fuel exploration, computer data processing, powerful analytical models, general scientific advances in geophysics, hydrochemistry, remote sensing and radio-active isotope use in the field. Improvements in drilling techniques, well design and construction materials, pumps and engines have lowered the average cost of pumped water considerably in the last three decades. Depletion and pollution of surface water and general concern and recognition of the value of improved drinking water supply have focussed attention on the economic and social benefits of groundwater as a source of potable water. In agriculture advances in plant breeding, fertiliser use, crop protection and other inputs and techniques which complement irrigation water have shifted upward the potential response to reliable irrigation.

In recent years there has been considerable development of groundwater for livestock in rangeland areas, particularly in Africa. Relatively small quantities of reliable water can transform the potential for extensive livestock development. Public control of groundwater sources (for example, by moving pumps) offers a neglected opportunity for maintaining optimum grazing patterns. However, the main focus of this study is upon irrigation.

Despite new opportunities and real progress in certain developing countries, there is understandable disappointment and impatience with the pace of rural development and with the neglect of certain areas or groups. The groundwater sector offers some hope but there are no panaceas for rural development. Certainly we cannot expect technical solutions to the basic problems of human values, ideas of morality and the development of social and political concensus that will determine the welfare of various individuals and groups within a country. Appropriate technology is often expected to fulfil broad development needs but it very often bears the stamp of a welfare policy - aimed at deprived groups and involving subsidies and transfers. Our premise to this paper is that there are opportunities for wealth creation using groundwater resources in which the incomes of the poverty group may be expected to increase in absolute terms and also it is conceivable that development of groundwater could provide a modicum of income for redistribution. However, many of the necessary regulatory devices are difficult and costly to apply. In this sector the trade-off between economic efficiency and equity, as normally defined, is sharp indeed.

In view of the present level of investment and the undeveloped potential, groundwater is of interest to a wide range of politicians, public officials and technical specialists in public health, agriculture, engineering and management. But the literature in relation to developing countries is sparse and scattered, with a high proportion of the most valuable material in inaccessible restricted reports. Often the literature is too narrowly specialised for the reader interested in the broad issues of groundwater system developments. It is to this general audience that this study is mainly directed.

2. SCOPE AND PURPOSE OF THE STUDY

This paper is a broad survey of economic aspects and policy issues that arise in development of groundwater resources in developing countries. It is intended to be wide-ranging but exploratory and not a comprehensive survey. The main focus is on the economic, technical and social issues which arise in conjunctive use of surface and groundwater for irrigation and other development purposes. The aim of the paper is then to formulate preliminary hypotheses relating to the crucial aspects of, and strategies for, groundwater development as they emerge from theoretical and conceptual considerations and a review of experience in various countries.

An analytical framework for testing such hypotheses will be presented. It is intended that subsequent verification will then enable guidelines to be prepared for the benefit of national bodies such as water development agencies, credit authorities, agricultural ministries and so forth, and also the bilateral and multilateral aid agencies who are equally concerned that effective, efficient and socially appropriate forms of groundwater development are carried out. The guidelines will be directed at technicians and planners involved in identification, formulation, appraisal and evaluation of projects involving groundwater development.

3. CHARACTERISTICS OF GROUNDWATER SYSTEMS

3.1 Physical Aspects

Water may be contained within spaces, interstices or voids in rocks and soil in one of five forms. In the zone of aeration there is soil water derived from precipitation or seepage from surface sources, vadose water held in part as films on the soil particles and capillary water connected in a belt lying above the groundwater proper. The zone of saturation contains the groundwater. Below this, in the lithosphere, there may be internal water in unconnected voids but this is scattered, small in total quantity, isolated from the hydrological cycle, of poor quality and of little or no importance for crop production.

Groundwater is found in permeable, generally granular, geological formations which act as storage reservoirs and, given lateral movement, transmission facilities. However there are also vast aquifers where water is stored mainly in fissures (generally limestones) and also weathered zones of semi-decomposed rock at the top of hard rock formations. Granites of central India are an example of weathered hard rock aquifers but equally limestones and dolomites often have such conditions. Groundwater storage can be managed so that there is a sustainable yield where inflow equals outflow or it can be mined.

An over-optimistic picture is sometimes drawn of the development potential of groundwater resources. Early experience with the good aquifers, which contain high quality groundwater lying close to the surface in places where crops suffer from occasional drought and where fertile soils exist (such as in large parts of the Indo-Gangetic Plain), can be very misleading if transferred without due modification to less favoured regions. For the most part, global groundwater resources are limited in relation to potential agricultural needs. Some are of dubious quality and the complex, costly technology for abstraction is often troublesome. Seldom do institutional means exist to ensure a fair distribution of the resource to all those who need it, and devising workable new institutions for this end has seldom proved satisfactory and often appears to be practically impossible.

3.2 Agricultural Needs

The economic problem is essentially to establish the best means to exploit the groundwater resource up to the point where the net returns are greater than the costs and, furthermore, where the net returns to any development are greater than alternative uses of the investment and recurrent resources. Analysts have to establish the most efficient means available for development whilst taking due account of the multiple objectives of public development policy. It is quite likely that the form and extent of groundwater exploitation will vary depending upon whether the options are viewed from a public or private viewpoint. If, in addition, in appraising investment options a social welfare function has to be maximised which takes a different account of benefits to, say, rich and poor farmers, or puts forward alternative resource ownership patterns to those obtaining at present, then the economic analysis problem is thereby immensely complicated.

Technical opportunites, economic and social conditions vary widely in tropical and arid zones. In this section a schematic presentation is designed to illustrate typical groundwater system characteristics which apply, at least in part, in most countries. This will provide a basis for any model to test development options for specific locations.

For the most part, this study concentrates upon tubewell extraction of groundwater. It should not be forgotten that the open well is an important source of water for small farms. In India at the end of the Fourth Five Year Plan the National Commission on Agriculture (1976) estimated about 6 million open wells, nearly two-thirds of which had either diesel or electric powered pumps.

A very large number of hand pumps, designed primarily for intermittent use for drinking water, are being installed in Bangladesh. A UNICEF supported Rural Water Supply Programme supplied 350 000 such wells over a 15 year period. When pumped for extensive periods these wells can abstract about 0.15 to 0.35 l/s and irrigate at most about 0.24 ha of wheat. It is estimated that in the 1980/81 dry (boro) season about 120 000 manually operated shallow tubewells were being used for irrigation (the term MOSTI has become the accepted name in Bangladesh for all handpump wells used for irrigation). These pumps have a number of desirable features which have considerable economic appeal. They are profitable to install and use. Recent estimates (World Bank internal documents 1980/81) indicate that a typical small farm would roughly double farm incomes and a public project would yield an economic rate of return close to 50%. Handpump wells (MOSTI) have an initial cost per unit of water pumped roughly equivalent to a shallow tubewell but, of course, they have no fuel bills for operation. They are locally manufactured and can often be installed by the farmer and readily repaired in local workshops. They are a suitable scale for even the smallest farm and the expensive pump component of the well can be fairly readily moved from one plot to another. This makes them particularly well suited for regions with fragmented farms. As they are hand operated, they generate considerable amounts of employment. However, hand pumping for long hours is perhaps the most arduous drudgery conceivable. Nevertheless, such simple, profitable scale-neutral technology has obvious economic appeal. The fact that thousands of such wells are being installed and operated by farmers is clear evidence of this.

It is difficult to obtain an unbiased assessment of the merits of this innovation compared with alternatives. There are few, if any, reliable measures of comparative costs. It is an area of debate that attracts partial 'mission-oriented' research. The fact that large numbers of farmers are installing hand pumps may reflect more a failure of the shallow tubewell technology delivery system than the attractiveness of hand pumps. Certainly the field failure rate of hand pumps is known to be high. For example, Anderson (1974) reports that in one thana surveyed only 100 out of 600 wells used for drinking water were working. Undoubtedly irrigation wells are better maintained than drinking water wells. It is known, however, that under intensive use problems in design, manufacturing, installation and operation and maintenance occur (Consumers Association, 1981).

There is no doubt that these hand pumps are privately profitable where the watertable is high, but they do limit the total amount of water which can be withdrawn. Where the watertable is below 6 to 7 m or where maximum use of the groundwater reservoir would require a temporary lowering of the watertable below this level, hand pumps cannot be used. Shallow tubewells have similar lift limits, but pumps can be sunk in pits to increase working height. Restricting technology to the low lift type limits the annual amount and peak supply level of water which can be withdrawn.

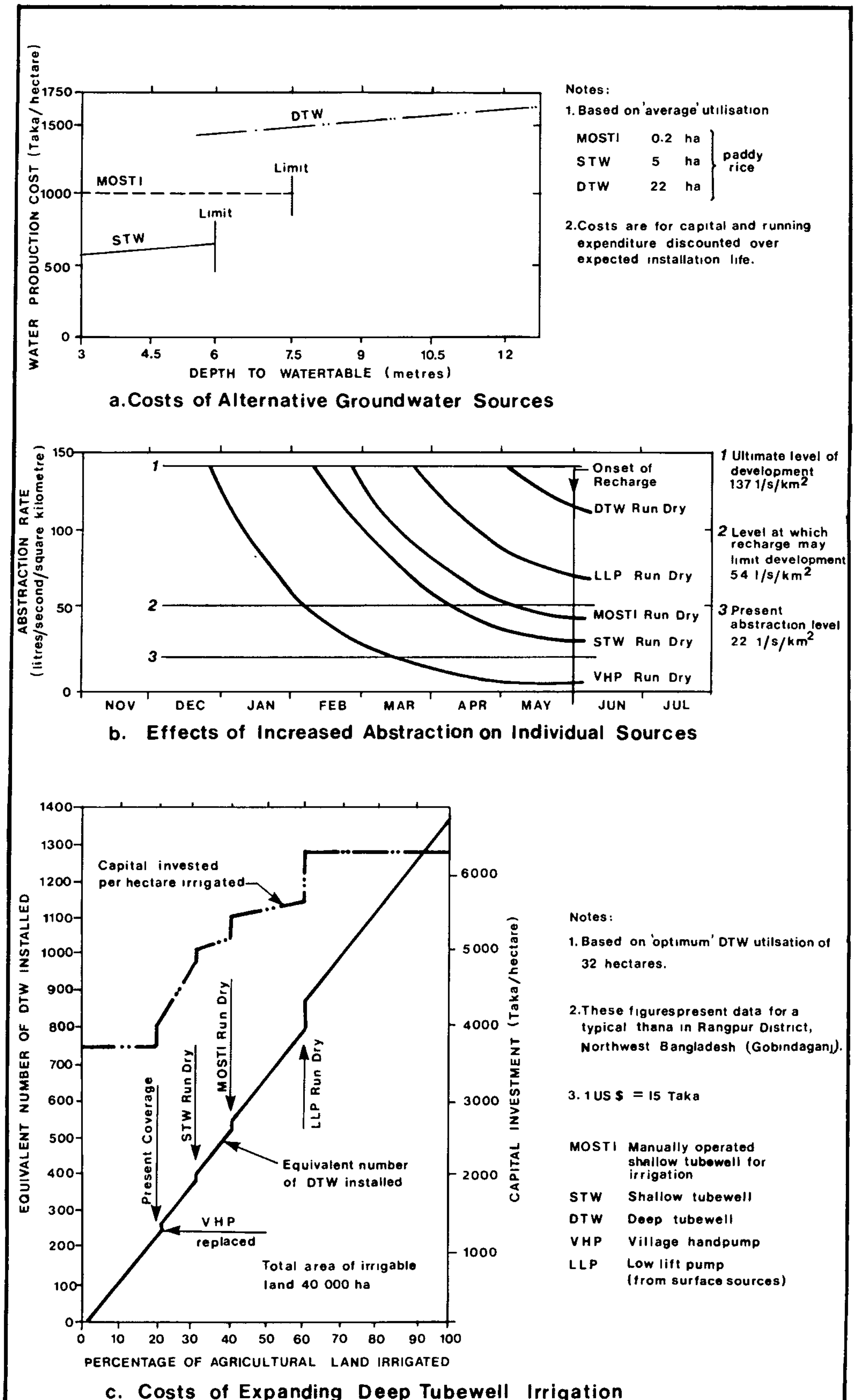
The shallow and deep groundwater development problem as it occurs in Northwest Bangladesh is illustrated in Figure 1. The data for this figure are derived from field studies from 1975 to 1977 (Cullen 1979). Figure 1a shows that shallow tubewells are potentially the cheapest source of irrigation but the amount of irrigation water pumped is limited by the pump lift of the surface mounted centrifugal and hand suction units. The installed capacity of shallow tubewells (STW) could be expanded to the same limit as the MOSTI but this would require sinking the pump in the well which would increase the costs. Figure 1b is from a case study in Gobindaganj thana. Cullen notes that :

> 'this demonstrates that all the existing irrigation sources can operate throughout the pumping season when fully utilised under upper quartile demand conditions. However, it is estimated that the shallower village hand pump will run dry in March.
>
> As abstraction levels are increased by further development, the overall depletion of the aquifer will result in progressive drying up of STW and MOSTI as shown. If present recharge estimates are found to be low, then further development will diminish river flows to the limit of low lift pump (LLP) operation. The ultimate level of development shown in Figure 1b is that required for complete irrigation coverage assuming that each deep tubewell (DTW) irrigates 35 ha and that 80% of the total area is irrigable. This could probably be achieved by installing deeper wells but economic justification would be required (particularly as the estimated life of the glass reinforced plastic well components used is much greater than that of the pumping plant, and periodic replacement would be far less frequent).
>
> The capital costs required for expanded groundwater development in Gobindaganj thana were also studied. The assumption was that, as shallow groundwater sources are dried up by increased abstractions, they are replaced by DTW. The results are shown in Figure 1c including the total equivalent number of DTW and the capital investment required (capital costs are for installations only and exclude irrigation distribution systems). This also demonstrates the need to plan the overall development levels. However, a 50% increase on present levels can be achieved with STW alone and much will depend on the availability of finance and the overall implementation planning.'

In round terms this case show that in this thana 20% of the land is irrigated. With full development using handpump wells or STW, 40% could be irrigated and with deep wells all the irrigable land could be irrigated. Several crucial questions arise if this is a typical case : can Bangladesh afford the additional costs of full DTW developments including the financial costs of compensation for dry shallow wells?; can Bangladesh afford to forgo perhaps half the irrigation potential as will occur if they develop only shallow groundwater sources?; would farmers be able to cooperate effectively to ensure full use of DTW sources or, conversely, does the individual control of a smaller cheaper supply from a MOSTI

FIGURE 1

Development Choices - Bangladesh



a. Costs of Alternative Groundwater Sources

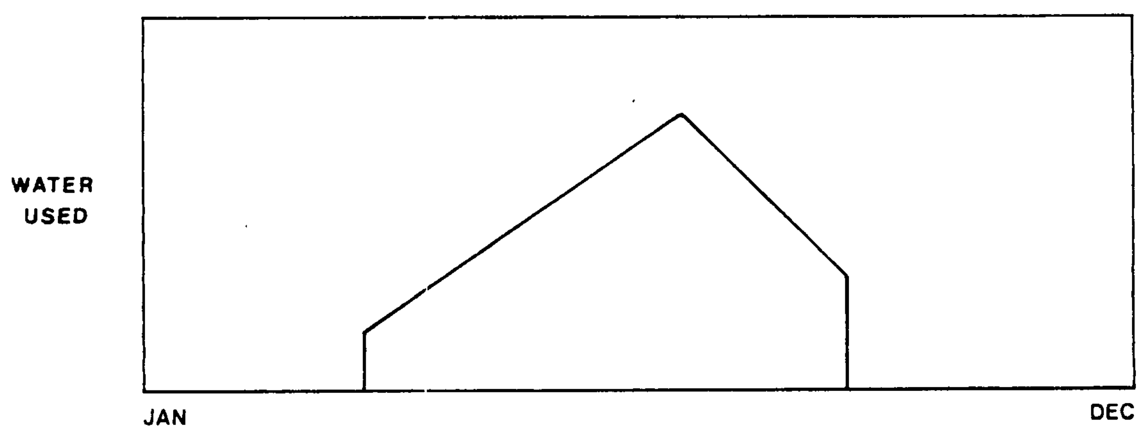
b. Effects of Increased Abstraction on Individual Sources

c. Costs of Expanding Deep Tubewell Irrigation outweigh the advantages of a larger supply from a DTW? Certainly there is not much time left in which to choose between these options because the form and extent of public and private investment are rapidly narrowing the range of options.

The Government has to choose between limited development of shallow sources using handpump wells or shallow tubewells, or more extensive development using deep wells. If hand pump development proceeds and is subsequently replaced by deep tubewells, then high financial compensation liabilities will have arisen. In addition, it is likely that there will be intractable administrative problems to ensure fair distribution of both financial compensation and replacement water for irrigation and drinking purposes. If maximum groundwater development is to be the main goal, then this should be undertaken before massive private investment is made. Alternatively, areas will have to be zoned for shallow or deep groundwater abstraction. Recent proposals taking this form have been presented to the Government of Bangladesh (MacDonald & Partners, 1980). Either option is fraught with problems. Optimum development of shallow or deep aquifers will require a degree of public control not yet evident in any area of rural development in that country.

In early stages of irrigation development farm water requirements follow this shape :

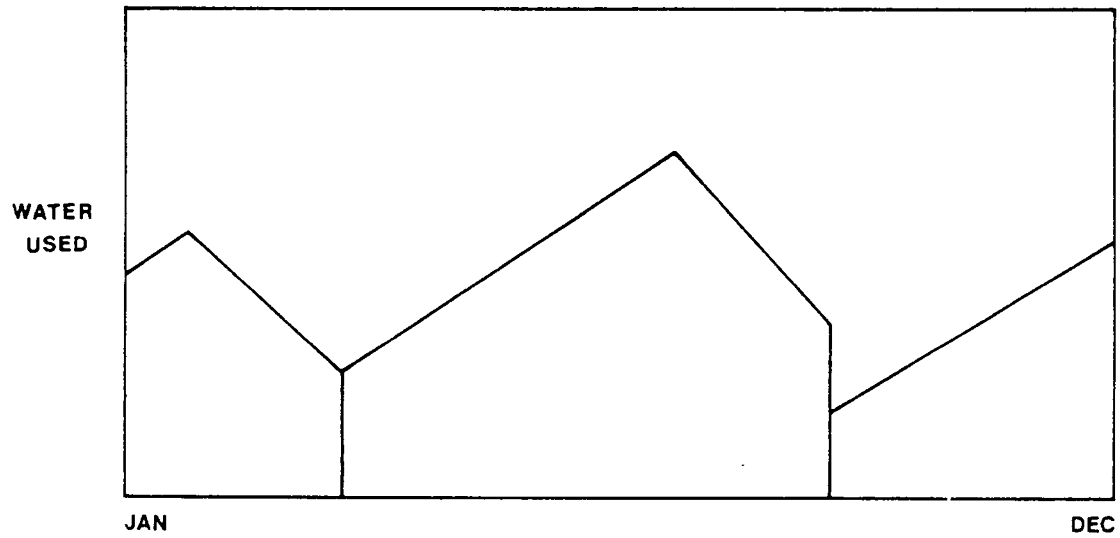
FIGURE 2



Note : No special significance should be attached to the April-September timing of this single cropping season, although this is the most common cultivation period in the northern hemisphere.

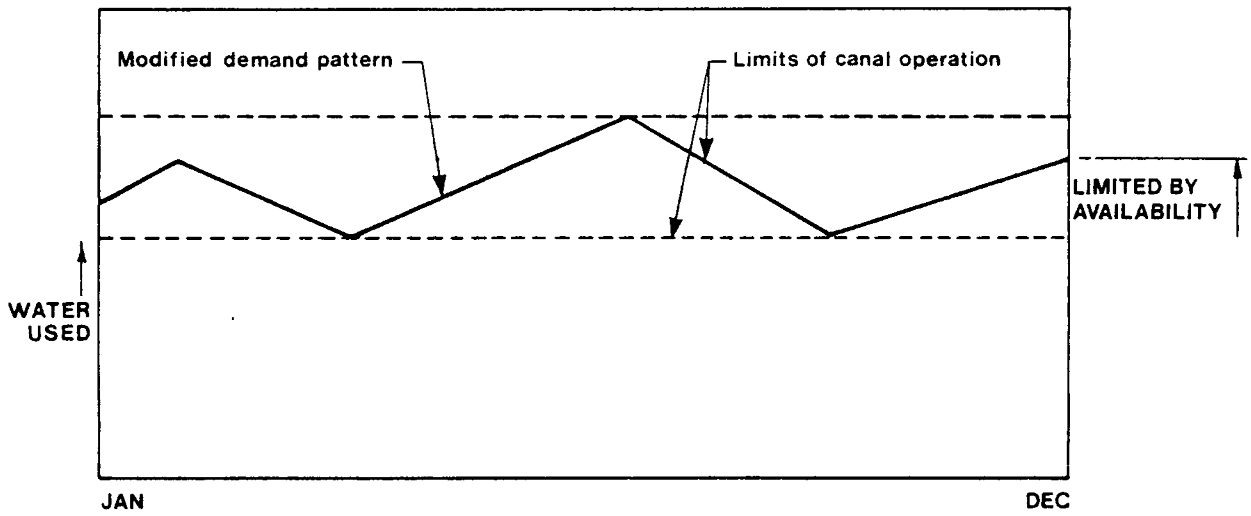
With increased agricultural sophistication double (or even triple) cropping becomes an option :

FIGURE 3



In arid areas this pattern of demand can be satisfied by rainfall, groundwater or canal irrigation. If rainfall is in some way inadequate, gravity fed surface canals are likely to be the cheapest option. This is not invariably the case. In some areas light soils, uneven topography or narrow commands make surface irrigation expensive or even infeasible. Furthermore, large fluctuations in discharge cannot be handled efficiently in canals and therefore this ideal peaked water demand is generally flattened in the following manner :

FIGURE 4

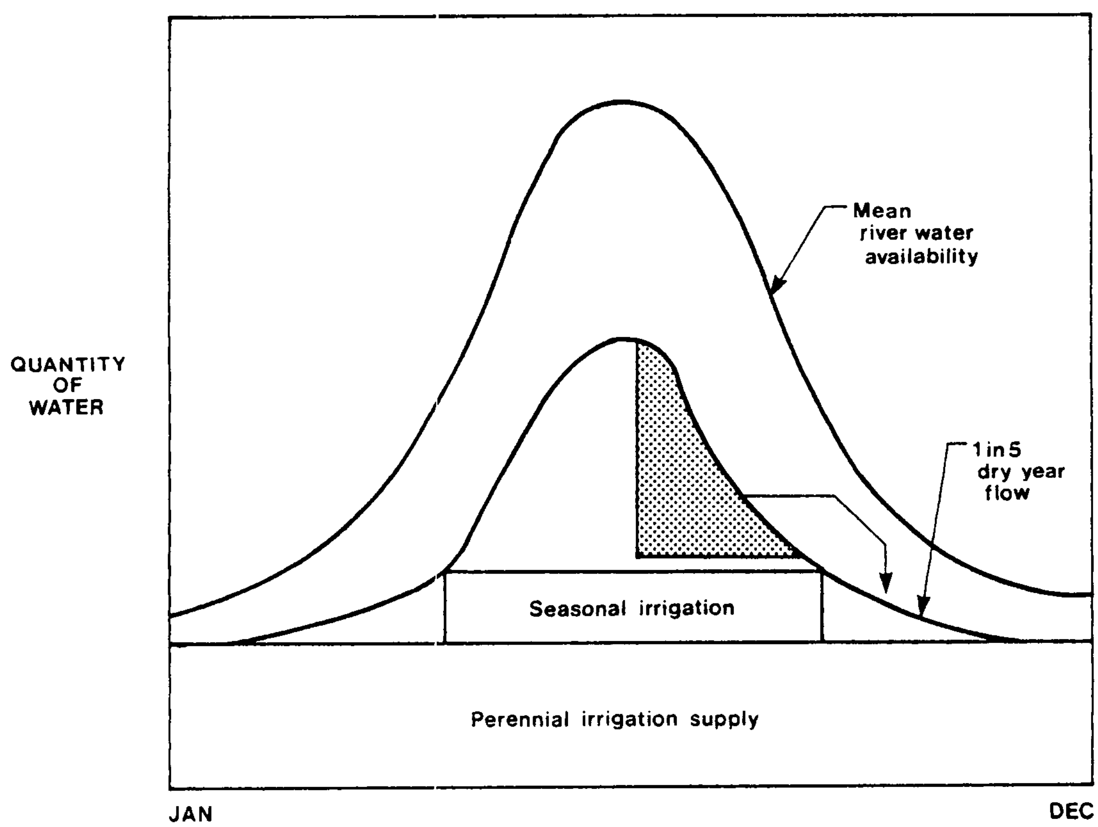


This 'flattened' pattern of water supply results in farmers not following optimal crop sowing dates, substituting less valuable but less water demanding crops, allowing crops to suffer stress at certain times and in other adjustments. The impact of shortage, of course, is lessened by the high water use efficiency obtained by farmers in times of scarcity. It is also possible to work with the concept of 'planned deficiencies' relying on the premise that the reduction in yield is not proportional with reductions in supply below the optimum. However, despite the obvious economic importance of such information, there are still inadequate data on the response of crops to various patterns of water shortage.

River water availability, often reinforced by the rainfall availability, typically follows a uni-modal pattern which contrasts with the bi-modal peak in cropping pattern water demand.

Perennial irrigation is then limited to the level of dry season flows. Where land is available, seasonal irrigation can be provided to grow, say, a single rice crop and possibly a second crop with residual soil moisture. Additionally or alternatively, some of the 'wasted' summer water (shaded in Figure 5) can be stored in surface dams to be released later in the year to service the more profitable double cropping and peaked pattern of water demand.

FIGURE 5



Such is the status of many surface irrigation networks. Groundwater exploitation can enhance the profitability of such agrarian systems in one or more of several ways :

(i) summer or hot season peak supplies can be met;

(ii) winter or cool season supplies can be met;

(iii) groundwater can be used and surface water diverted elsewhere or retained in dam storage for periods when hydro-electricity demands match agricultural demands;

(iv) in dry years deficits can be met;

(v) if (i) + (ii) + (iii) + (iv) are less than recharge and the watertable rises, then drainage water can be pumped in non-irrigation season; if (i) + (ii) + (iii) + (iv) are greater than recharge, then excess surface water, which would otherwise be discharged to the sea, can be diverted into fields for leaching any salts or, perhaps more important, to increase recharge.

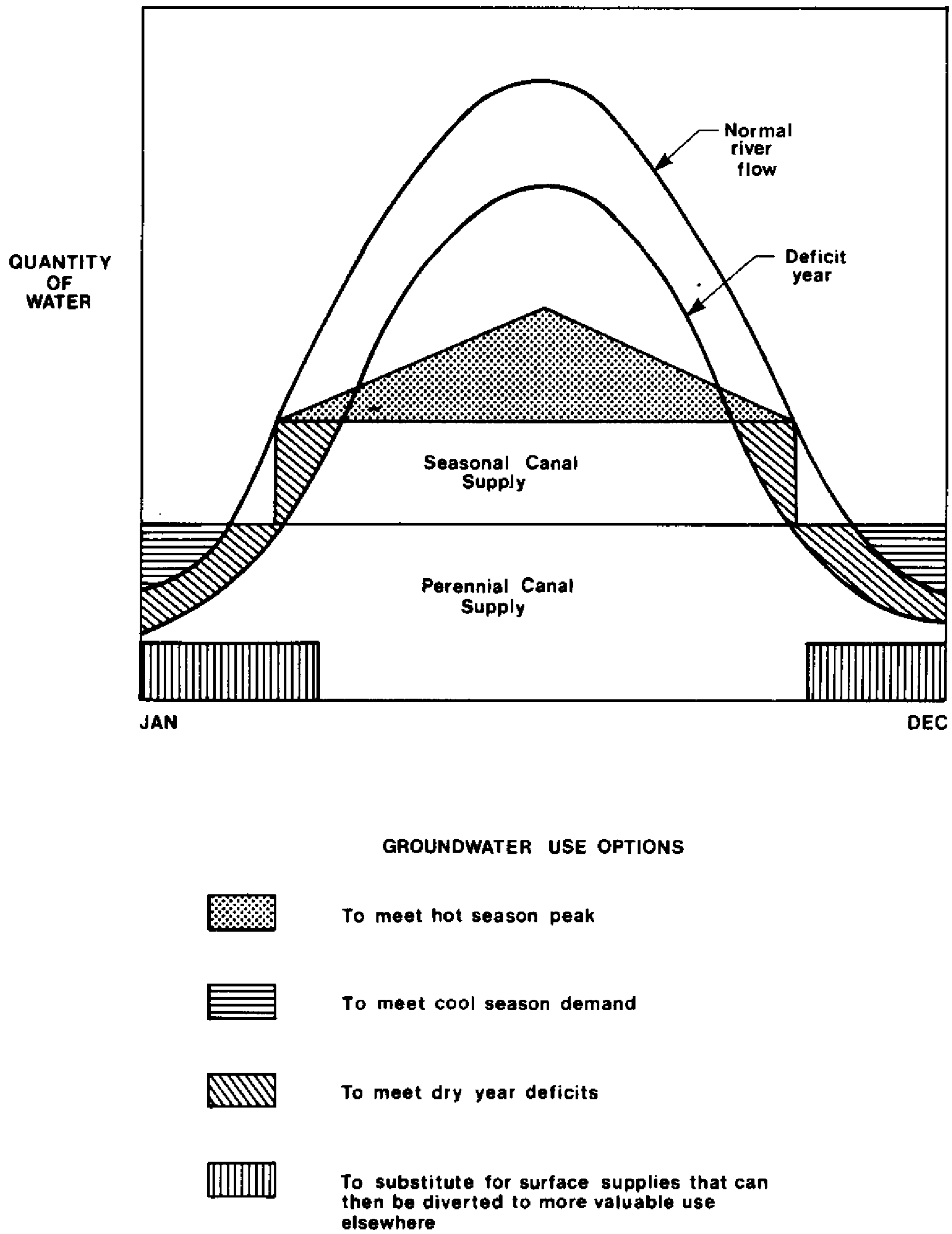
These options are illustrated in Figure 6.

Tubewell irrigation is employment creating. Tubewells can help offset the labour displacing effects of tractors and other forms of farm mechanisation. For example, Agarawal (1981) finds for HYV wheat cultivation in the Punjab that, whereas tractor ploughing, tractor sowing and power threshing diminished labour use by 82, 24 and 4% respectively, tubewell irrigation increased employment (on all farm size groups) by an average of 89%.

The quality of groundwater almost always gives grounds for greater concern than surface water. Long term use without careful control of leaching will lead to a salt build-up in the topsoil. Quite frightening amounts of salt are involved. A wheat crop grown with water of 1 000 ppm will add more than 8 tons of salts per hectare each season. Topsoil will only remain usable in such circumstances if adequate quantities of water are provided for leaching (as happens all too often when fields are over-irrigated by farmers!). In addition, watertable levels must be depressed so that there cannot be a reverse, upward movement of salts in solution in the capillary water. Further, even where watertable is deep and salt is leached out of the root zone, there is a danger that following rain or heavy irrigation, salts will go into solution and be drawn into the root zone when sufficient insolation occurs.

Canal closures for routine maintenance of surface irrigation structures and desilting of canal beds are normally scheduled according to procedures established in the planning phase of surface water development. Such maintenance generally takes two to four weeks. Although this activity is normally undertaken during cold weather, when crops require least water, or during rainy periods, harmful moisture stress can occur and it may not be possible to apply fertilisers at the optimum time. Recent agricultural developments, such as short duration crops, day length insensitive varieties and the adoption of new exotic crops, often have the effect of making traditional canal closure periods inappropriate. These are difficult to re-schedule. Indeed, for modern irrigated agriculture, with its high cropping intensities and demands for regular timely water, it is difficult to specify any appropriate two or three weeks period for closure. The inappropriate duration and timing of canal closure is now evident in the Indus Basin. In these circumstances the value of groundwater, as a second source of irrigation water, is considerably enhanced.

FIGURE 6



3.3 Operation Advantages

Where canal operation or rainfall is irregular and unreliable, the ability to exploit groundwater is a valuable insurance. It is a costly and unjust occurrence that, at a time when the potential returns to reliable irrigation are shifting to a new level (a higher production function) as a consequence of scientific advances, evidence is increasing that canal operation is subject to grave defects (Hashim Ali 1981, IRRI 1980, Chambers 1981). In such conditions tubewell development is a safeguard against failure or shortfall in surface irrigation supplies which may give high returns. Much of the apparent profitability of groundwater development in the Indian sub-continent is really a reflection of the real costs of substandard working of the surface irrigation network.

In such circumstances the normal criterion of tubewell efficiency, namely high operating hours per year, will be an unreliable guide. Tubewells operated for short periods to give reliability to either canal or rainfall supplies will be effective investments. This risk reducing role of tubewells has been demonstrated in Indonesia and in Pakistan (Lowdermilk et al. 1978).

Groundwater development can proceed at spectacular rates without direct public support. In the Kosi Command in India, Clay (1981) notes an increase in tubewells from about 3 000 in 1969/70 to almost 60 000 in 1977/78, whilst the public development of the Kosi Canal System, opened in 1964, did not manage to reach even 20% of original design levels. This provides an example of wasteful and ineffective public investment and profitable private investment. Whilst private tubewells were being sunk and efficiently operated, the canal exhibited typical problems, albeit on a grand scale, including over-optimistic land capability assessment, excessive silt deposits, lack of drainage and subsequent waterlogging, long and poorly timed closure periods, water rate collections running at about one-third of estimated due charges, and managerial problems related to a lack of sympathy and understanding for agriculture or even for management functions, and extremely weak incentives to staff for efficient operation.

Groundwater can reduce or eliminate the need for dams, canals and pipelines. Investment can then be phased in line with demand. The financial problem presented by excess capacity in the early years of operation of a dam project is thus avoided.

The advantages of phasing are often given undue weight in economic analysis by use of high discount rates which 'diminish' future tubewell investment and the relatively high recurrent costs. All too often this illusion is shattered when, with the passage of time, the full monetary value of these expenditures has to be found.

Groundwater offers other advantages over surface canal irrigation. Smaller packets of suitable land can be more economically irrigated by groundwater than with surface systems. Normally a tubewell system can be designed to suit any area and topography.

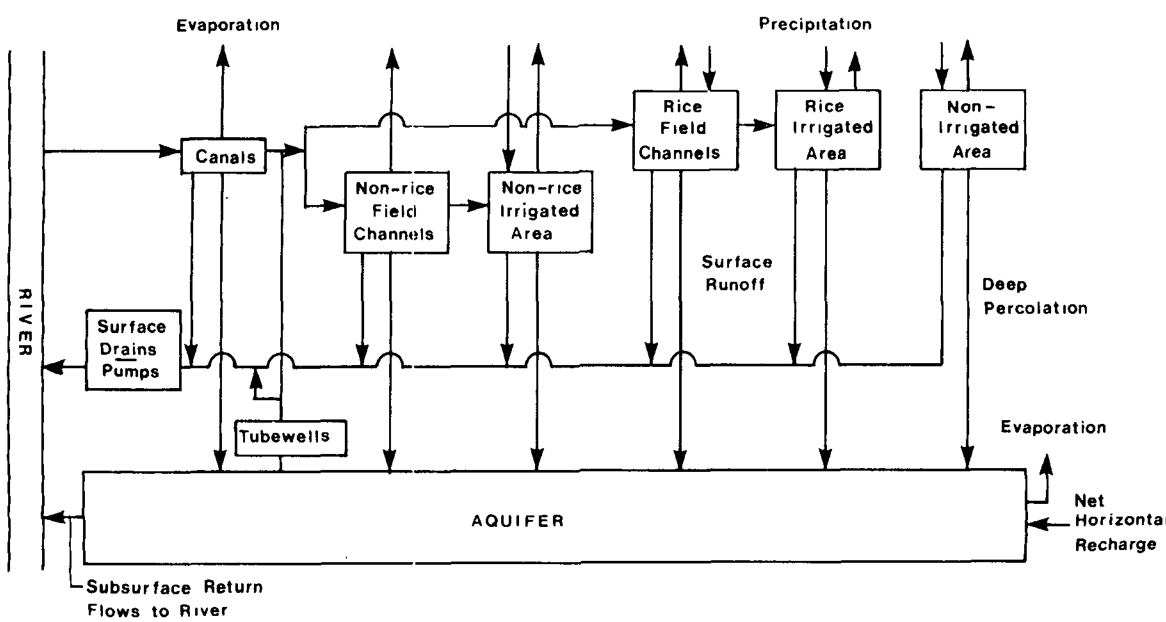
Land distant from rivers can also be economically irrigated and the lower rates of distribution channels to irrigated fields may crucially affect the economics of lining distribution channels. Wells can be located in high areas or at the tail of canals where surface irrigation tends to be in short supply or delivered late. Where wells recover drainage and seepage water from the irrigation system the overall system efficiency of water use typically rises from about 50 to 80%.

Irrigation supplies can be augmented using groundwater with the minimum disturbance for existing surface irrigation. Canal remodelling to take higher surface discharge disrupts agriculture more substantially than groundwater development. Canal supplies can also be augmented by saline groundwater providing that sound blending procedures are adopted.

Groundwater resources are made up of various mixes of stock and flow resources. In the simplest case, a single well will tap a limited aquifer without recharge or interconnection with other wells and the investment decision hinges on the question as to whether the sum of net benefits from using the groundwater, suitably adjusted for the time they arise, exceed the requisite margin of the development and operation costs over the life of the well. At the other extreme there is the type of complex system, illustrated in Figure 7, where numerous farmers tap the same aquifer. In such a system, recharge is an important part of the resources, and the optimum mix of seasonal and perennial irrigation, the overall extent of rice cultivation and other decisions in turn influence the amount of water available for irrigation and the drainage requirement.

Figure 7 represents the situation obtaining in Bangladesh (Smith 1970) which is typical in large areas of India, Pakistan and Indonesia where a significant proportion of the world's underdeveloped groundwater resources lie. With such a complex interdependent system a simple budgeting approach to assess alternative patterns of development is likely to be slow, inefficient and possibly unsuccessful.

FIGURE 7



However, specification of a valid model of the total system components, the inputs, the pattern of demand over time and the economic returns is difficult. The models used are generally partial, deterministic and static but the system being described is stochastic and dynamic. The agricultural water consumption process is sequential and a single decision period cannot reasonably exceed one month.

Much of the data required to make the models operational and to validate them are either not available or not well-founded. For example, estimates of the specific yield of the aquifer, the seepage losses from canals and the effect of variation in watertable levels upon seepage, although crucial, are notoriously unreliable. On the output side the production functions, or crop responses to various watering regimes, are extremely ill-specified and generally related to atypical research station conditions. However, it will be argued that the modelling process, for all its present deficiencies, forces the analyst to ask relevant questions, to identify the crucial aspects of the system, and to think more rigorously about the inter-relationships between the system components and effect or variations in key variables. As with many operational research techniques the discipline is normally more valuable than the answer.

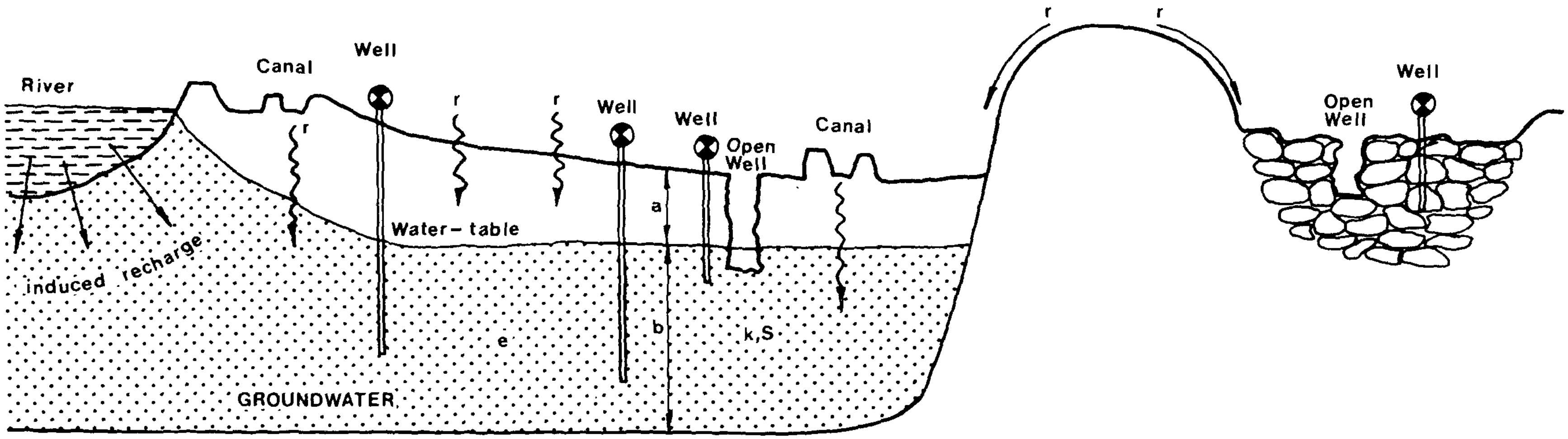
3.4 Aquifer Characteristics

Figure 8 illustrates some of the vital characteristics of the typical groundwater system that influence the form of development. For practical purposes any groundwater level below 8 m can be regarded as deep. Water levels may fluctuate over a year or a long cycle, or they may exhibit long term secular falling or rising trends. Since pumping costs are directly proportional to height of water lift and deep wells are clearly more costly to drill and equip than shallow wells, depth to watertable (a) is an important characteristic. The depth of the aquifer (b) influences the options for development together with other aquifer characteristics (c) of which the permeability (transmissivity divided by aquifer thickness) and porosity are important. In Figure 8 the aquifer is not confined under any pressure exceeding atmospheric pressure by an overlying impermeable layer or bed. This water enters the groundwater system by natural and induced recharge (d) from precipitation, run-off from hills and rocks, seepage from rivers, canals and irrigated fields. Natural recharge varies from month to month depending upon supply and there is considerable year to year variation. Open wells (f) with shallow access to the aquifer are vulnerable to falls or to fluctuations in watertable.

In aquifers, such as that shown on the left of Figure 8, which have high transmissivity, pumping of deep or even shallow wells (f) can cause a local or, when withdrawals exceed recharge, general fall in watertable levels. In rock or clay aquifers such as illustrated on the right, each essentially taps its own limited storage voids. Large parts of Africa and the hard rock areas of India, which comprise a significant part of the area of India, have aquifers of this type. The limited yield of water from shallow aquifers and aquifers of low storage capacity and transmissivity have led to their neglect by public authorities. Farmers have found that even small quantities of water, judiciously applied, alongside modern inputs, are often extremely profitable. Simply constructed open wells, storage cisterns and locally manufactured wells, pumps and engines are employed to obtain early crops, to extend the cropping season, to help cope with temporary water stress in the growing season and to obtain

FIGURE 8

Important Characteristics of Typical Groundwater Systems



r – natural recharge
a – depth to water table
b – depth of aquifer
k,S – aquifer properties, permeability, storativity
e – water quality

high yields and high quality. Examples which indicate the agricultural value of relatively small amounts of groundwater can be quoted from agricultural areas as varied as Cyprus, Saudi Arabia and India.

The fact that recharge can be increased, in some circumstances, by lowering the watertable is worth noting as this characteristic, with suitable investment and management operations, can be employed to increase the quantity and value of groundwater pumped. The economics of lining canals and farm distribution channels will be influenced by the feasibility and cost of re-use of seepage water. Where drainage is an agricultural problem, it is crucial to know the sources and level of recharge before remedial works can be designed and appraised. More generally, the complementary benefits to be obtained from joint planning of surface and groundwater investment and operating policies should be foremost in the minds of water resource planners.

3.5 Economics of Wells and Wellfields

This discussion is confined to drilled wells because it is in this respect that economic decisions can really affect the manner of development of the world's large aquifers, especially in the developing countries. This is not to say that there are no economic considerations involved in the vast number of hand dug wells operating in such countries, but only that they are less susceptible to this kind of analysis and such economic decisions as are necessary are best made locally.

As far as bored wells are concerned, there are considerations of drilling techniques, configuration of wells, materials to be used, the type of pumping equipment, and the type of prime mover.

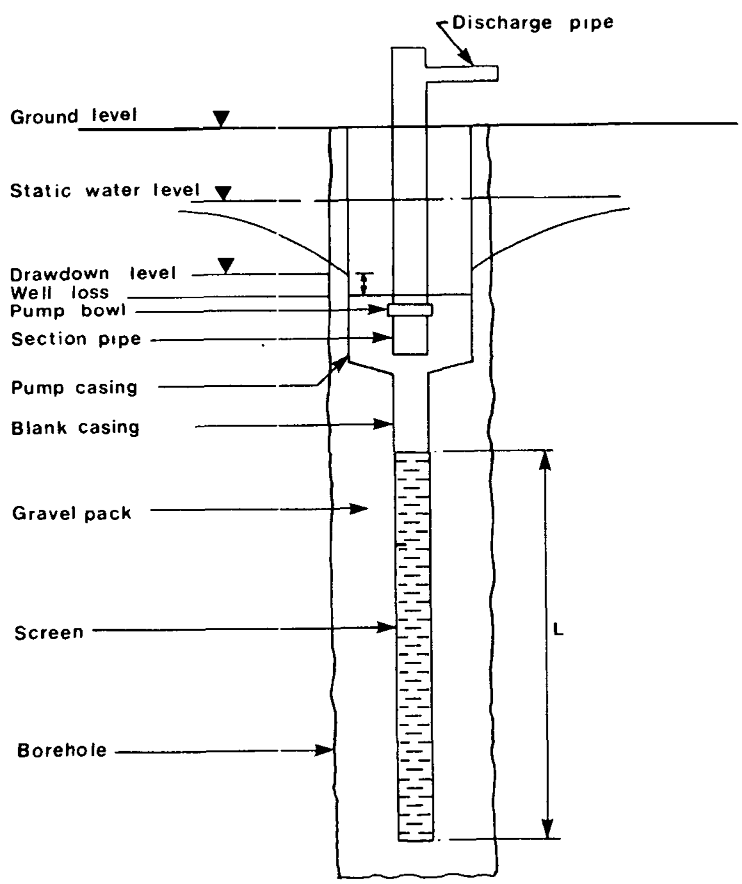
Drilling techniques for water vary from the simplest hand operation to the most sophisticated drilling rigs similar to those used by the oil industry. The traditional percussion system involves repeatedly raising and dropping a cylindrical tool on a rope down the hole, most often with a steel casing following immediately behind. Many simple wells for domestic water supply to a village or a farm are put down by hand using a tripod with a pulley to support the rope. For larger wells tripods with a motor may be used or, where speed is more important, a truck-mounted percussion rig is employed. This method can be used in alluvium, boulder beds or weathered rock. It is slow and cumbersome, but effective, and is still widely used. The simplest operations are cheap, labour intensive and require relatively little skill. Technically there is one advantage in that it is possible to recover reasonably good formation samples.

Rotary drilling is the other main technique and again this can be simple, as seen in Bangladesh, where a pipe is used with teeth cut at one end and supported on a bamboo tripod. Wooden arms are attached in the form of a cross and four men turn the pipe while water is pumped down the centre. This method is crude, but many good wells have been installed in this way in alluvial formations. It is cheap, labour intensive, and, as little skill is required, local labour can be used effectively. Unfortunately this method is slow and almost invariably produces a crooked hole. With conventional rotary drilling, using large truck or trailer-mounted rigs, a drilling fluid is nearly always used. This may be water, mud, air or foam, and all of these are used in the direct circulation method where the fluid is passed down the hollow drill pipe, goes through the bit and then, by way of the annulus, between the drill pipe and the wall of the hole. Reverse circulation, involving the opposite mode to that described above, is often used for large diameter wells in alluvium using water as the drilling fluid. Rotary methods are quick and can be cheap if a large number of wells are involved. Virtually all serious work on groundwater projects is done by one or other of the rotary techniques.

In hard rock rotary methods using direct circulation are generally preferred and this is the common method used for deep wells (up to 2 000 m) in Saudi Arabia and for the much deeper wells used in oil development. A variation, which in some ways is a combination of rotary and percussion methods, is the "down-the-hole-hammer" method. This involves a compressed air hammer suspended on the end of the drill pipe with the escaping air carrying up the cuttings to the surface. It is commonly used in very hard rocks such as granite.

After drilling a well it is usual to place an upper casing in which the pump is set. For wells in collapsible formations, further casing and screen is suspended below the pump casing. For some fissured rock formations no screen is necessary. Where screen is used, it is placed opposite the best potential producing zones and blank pipe placed elsewhere. Sometimes the screen is sufficient on its own to retain the formation particularly in coarse sand and gravel aquifers, but in finer formations it is necessary to install a gravel filter between the screen and the hole sides. In this case a larger drilled hole is necessary to ensure an adequate thickness of filter. Figure 9 shows a typical well including all the elements described above, and this would be the normal type found in alluvial flood plains.

FIGURE 9



Casing and screen materials have been the subject of debate between the advocates of local traditional materials and those supporting modern long life and high performance components. There is no single answer to the problem. Local farmers who install wells at their own expense invariably go for low first cost materials and seem to accept the fact that there will be a high rate of failure. Public authorities go for safety because they cannot afford the public castigation that would result from a high failure rate.

There is fierce competition between the various screen manufacturers and dubious claims are often made extolling the alleged virtues of particular materials and designs. Frequently the very simplest slotted pipe is quite adequate for the purpose but occasionally special materials and screens with a high crush strength are necessary. In very deep wells in rock the screen is only a small percentage of the total cost and then it is often wise to use the best materials. In contrast, reasonably cheap plastic, steel or glass reinforced plastic (GRP) screens are adequate for the thousands of wells installed for irrigation that are typical of India, Pakistan, Bangladesh and Indonesia. Much has been written about open areas of screen and how large open areas have improved hydraulic efficiency. In spite of all manufacturer's literature it can be said unequivocally that large open areas hardly affect the hydraulic efficiency of a well at all. Field and laboratory measurements have demonstrated this fact beyond doubt. However, if wells are subject to blocking through incrustation of the screen slots, then there is clearly a case for the larger open area, provided that the premium is not excessive. The Khairpur Project in Pakistan provides field experience with large open area stainless steel screens and slotted GRP. Although the wells have deteriorated in performance with the passage of time, there is no difference between one type and the other. If anything, the GRP is very slightly better.

One area that still requires study is the effect of rehabilitation techniques on various screen designs and materials. Regrettably no serious well rehabilitation has been carried out in the developing countries which can be drawn upon. However, techniques are well established in developed countries, particularly in the USA.

The whole subject of screens and materials is very wide in scope and would require a treatise on its own to do it justice; even to list and describe all the various types that the authors have encountered would require a wider canvas than this paper can provide.

Pumping equipment too offers economic choices. The possibilities are force, surface mounted centrifugal, turbine or submersible pumps. Force pumps are conventionally only used for shallow water wells and are operated by hand or the 'nodding duck' type pump for deep oil wells. Centrifugals are the most common type for shallow wells or indeed anywhere the pumping level in the well is not more than 7.5 m (25 feet) below the pump. Sometimes this type of pump is placed in a chamber below ground so that it can deal with deeper watertables. In large dug wells it may be even floated on a small pontoon. This is the cheapest type of conventional well pump and is often manufactured locally in the developing countries. Deep well turbine pumps are next in popularity and can be used where deep settings are required. All of these pumps can be powered electrically or with diesel engines. The submersible must be electric because pump and motor are close coupled and the whole unit placed down the well. If electric power is available, then a careful analysis must be made to compare turbines and submersibles. Generally at the deeper settings (greater than 100 m) submersibles are now becoming cheaper, but each case must be examined on its particular merits. One of the advantages of a submersible is that it will work satisfactorily in a crooked well where a turbine pump with its long shaft will have a very short life.

Well waters can be very corrosive and all component materials including screens, casings and pumps must be considered from this aspect. It is essential at the investigation stage that the chemistry of well waters should be examined at the well head in respect of Eh, pH, bicarbonate and dissolved carbon dioxide, as all of these parameters are involved in the corrosivity of water and they all change en route to the laboratory.

The cost of groundwater projects, particularly projects involving wellfields of several hundred wells, such as those which can be found in the Indian subcontinent, can be greatly reduced through economic design. For a single well in a thick aquifer there is a definite design choice between capital and annual expenditure. A deep well with a greater screened area will have less drawdown than a shallower well for a fixed discharge rate. Thus the deeper well will cost more initially but by virtue of the lesser drawdown the annual running costs will be less. Somewhere there is an optimum depth. This is determined by a discounted cash-flow method. For example, it can be shown that, for the case illustrated in Figure 9, the present value, PV, of capital plus running costs is given by :

$$PV = C_1 + C_2L + C_3Q + C_4 \frac{PQ}{L} + C_5 \frac{PQ^2}{L} \qquad ......(1)$$

Where $C_1 - C_5$ are constants depending on the costs of drilling, screen, fuel, etcetera.

Q is the well discharge rate

L is the screen length

P is derived from the empirical relationship (in F.P.S. units) Drawdown = $1.32\ Q/_{KL}$ = $PQ/_L$ which has been derived from a large number of well tests

K is the aquifer permeability

The present value can then be partially differentiated with respect to any of the variables involved and equated to zero to determine the value of that variable for minimum cost. For example :

$$\frac{dPV}{dL} = C_2 - \frac{C_4PQ}{L^2} - \frac{C_5PQ^2}{L^2} = 0$$

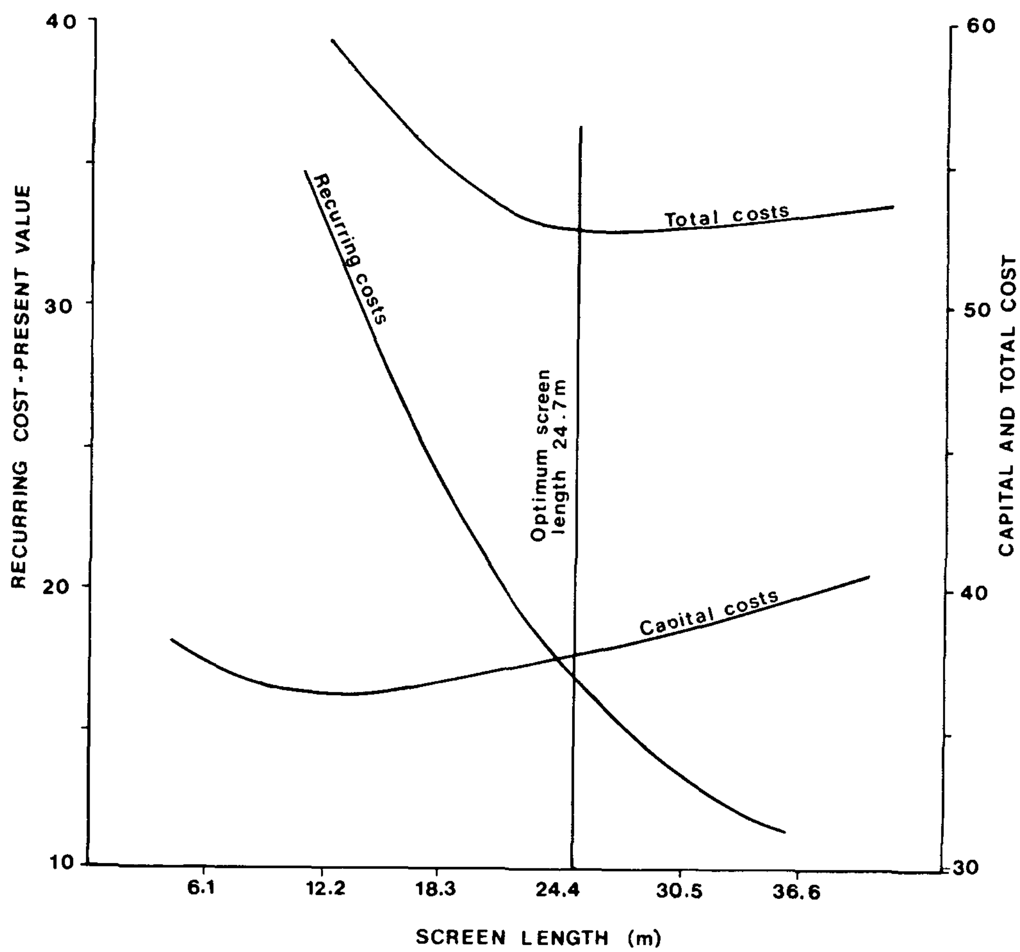
$$L^2 = \frac{PQ}{C_2}(C_4 + C_5 Q) \qquad \text{......(2)}$$

Thus the optimum length of screen can be calculated for any well discharge. Figure 10 shows a plot for optimum screen length with the capital and running costs separated.

A similar procedure can be used to optimise well diameters and discharges (Stoner et al. 1979).

These economic well design principles were first developed for wells in the extensive uniform alluvial aquifers of the Indus Plain and it could be argued that such design criteria are not applicable in those areas where well screens are generally not used or where the aquifers are neither uniform nor extensive. The authors would suggest, however, that a closer regard to economic design is important in all cases of groundwater development. It is now widely recognised, for example, that the active, more transmissive parts of the Chalk and Bunter Sandstone aquifers of England are restricted to the upper hundred metres or so of each aquifer. Connorton and Reed (1978) have shown that the permeability of the Chalk in the Lambourn Scheme is essentially zero below 70 metres from the surface. There is therefore clearly an optimum depth to wells in the Chalk and the Bunter and this fact should be taken into account in future well designs.

FIGURE 10



In the case of whole wellfields, economic design may be even more important because well spacing has also to be considered. This greatly affects the regional drawdown and thus the pumping costs. In a uniform aquifer the regional drawdown can be calculated but more often a model of the system is needed to compute the effects. With projects involving wellfields connected by pipelines the length of pipe and its diameter become important factors in the optimisation of well spacing. A complex wellfield pipeline system can only be optimised by the use of a computer to examine all the options and to minimise the present value of the proposed system.

Concluding this section there are clearly economic choices to be made. First, whether the project is to be developed by local farmers using traditional techniques (IDA Agricultural Credit Projects in India and elsewhere), or is it to be a public project with international contractors and modern techniques (for example, IDA loans to Pakistan SCARP Schemes); issues related to this question are elaborated later. In either case are economic analyses in the design of the project given full rein? Secondly, are materials and pumps specified likely to result in the lowest overall discounted cost per volume of water delivered? Are diesel engines or electric motors with the concomitant power lines and side benefits likely to be the most beneficial for the rural population? In choosing a technique, will labour intensive methods be appropriate or will earlier completion of the project, that modern methods might bring, ensure an earlier and higher overall involvement of labour.

3.6 The Use of Wells for a Dual Purpose - Drainage and Supply of Irrigation Water

Drainage is probably the major problem with the world's irrigation systems, although the technical aspects of the problem are well understood. The great demand from farmers is for extra irrigation water, and politically it is opportune to support such a demand, irrespective of the insidious damage caused by adding extra water to a system without drainage. Drainage has no glamour and the overall benefit is long term and difficult to see, especially in the eyes of subsistence farmers.

We believe that investment in drainage, particularily at the time of original project construction and for the intensive forms of irrigation now generally being advocated, is likely to pass tests of economic feasibility. This hypothesis gets scant treatment in planning documents and is even neglected in some irrigation rehabilitation projects. As the trend for increased irrigation intensity and more multiple cropping continues, the need for drainage is enhanced but such conditions also lower the per hectare or per crop costs of drainage. The economics of drainage of irrigated lands is a subject worthy of more research and practical attention.

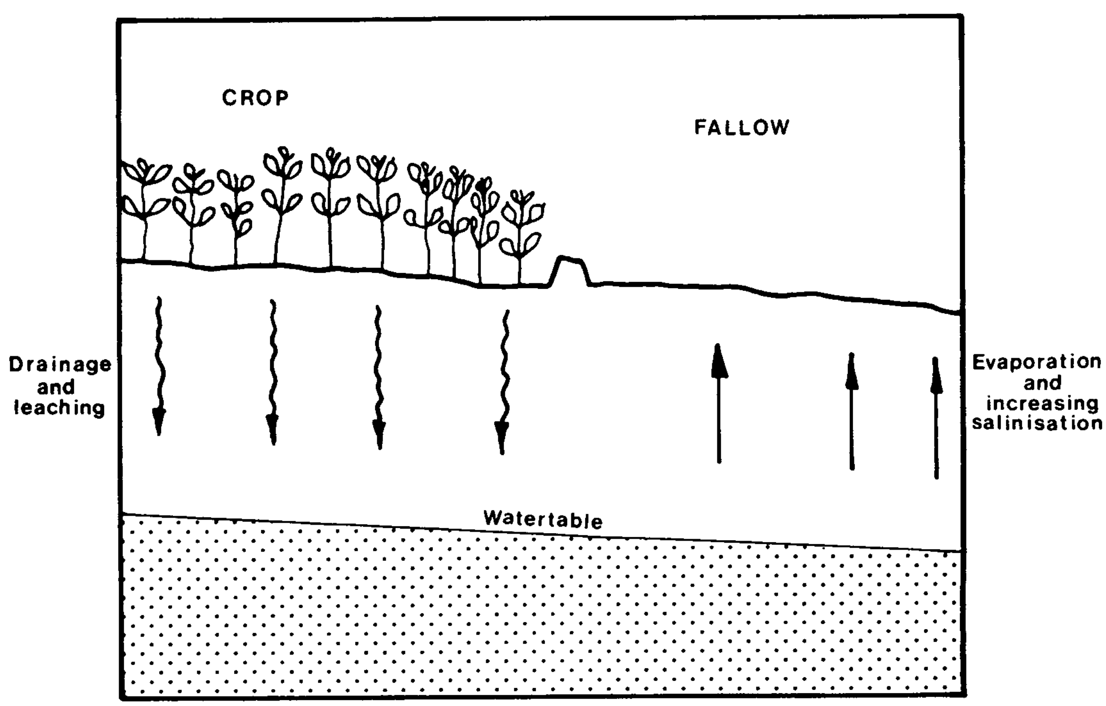
Neglect continues into the operation phase. Conventional drainage schemes, even where they exist, notoriously suffer from lack of maintenance and inevitably are the first casualties of budget reductions. The minimal benefits (or even increased costs if, for example, poorly maintained drains are a source of debilitating disease) which are likely from a poorly maintained drainage network will reinforce the predjudices of those who give drainage investment low priority for investment funds.

It is questionable whether a conventional drainage system involving tile or open drains is anyway satisfactory in arid regions with low cropping intensities. The problem revolves around the necessary minimum depth at which the watertable must be established in order to avoid serious reductions in the yield of crops and to avoid building up damaging salts in the soil profile to the extent that reclamation is no longer feasible.

These eventualities are dependent upon crops grown, soil type, evaporation potential, depth to watertable and the quality of water at the watertable surface. The latter is controlled by the intensity of cropping and the excess quantity of water applied to the crop that drains below the root zone.

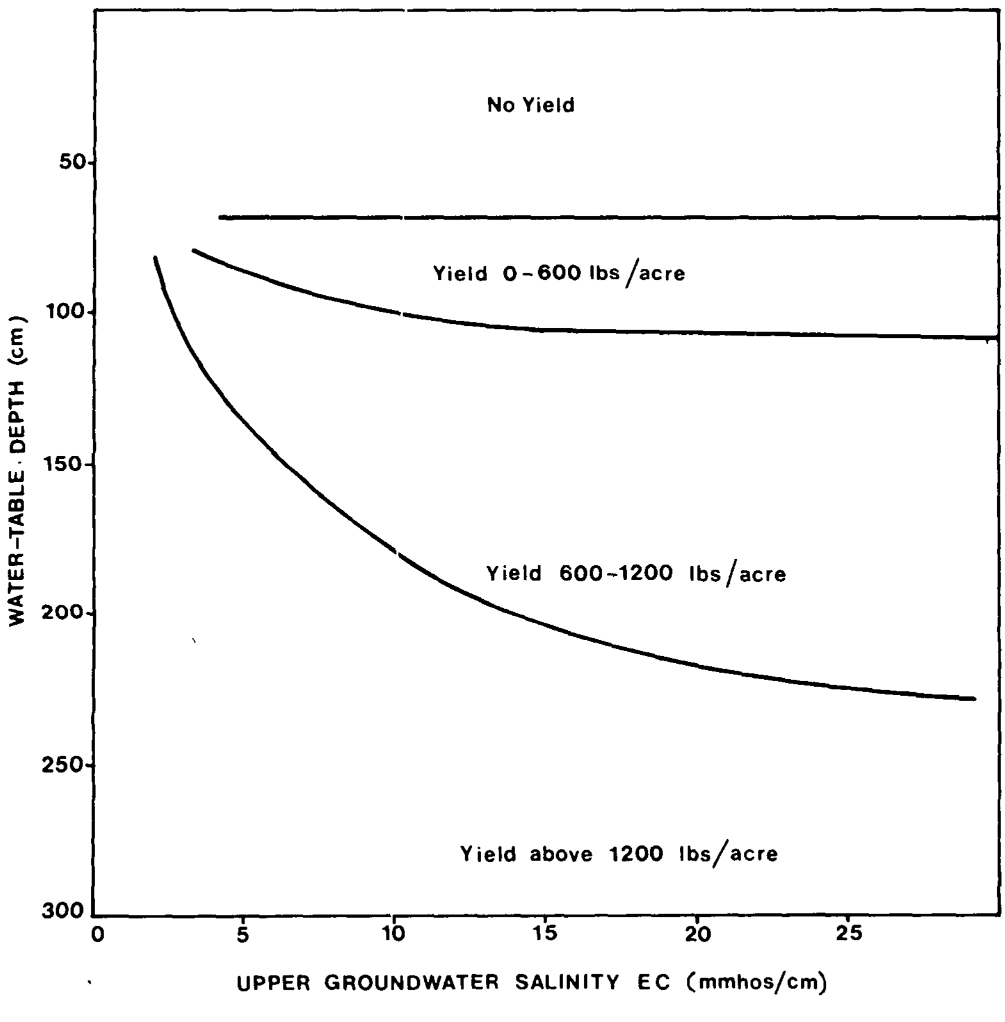
Crops have different rooting depths and thus wheat can be grown successfully with watertable depths nearer the surface than cotton. But for any crop the depth at which the watertable is established for successful growth is dependent on its salinity. Wheat might therefore be grown with a watertable at one metre (three feet) if the groundwater is fresh, whereas it may require two metres (seven feet) if it is very saline. Soils affect the issue in several ways. Sands are free draining and thus easy to keep well leached providing the watertable is kept sufficiently deep by natural or artificial drainage. Sandy soils also have a very small capillary rise and so evaporation losses are less at practical watertable depths. Further, the saturated zone above the natural watertable level is almost zero, and thus the crop can tolerate higher watertables and even more saline irrigation water. Clearly in hotter climates water evaporates more quickly and, in evaporating, salts are left behind in the soil profile. The nearer the watertable is to the surface the higher the evaporation and hence the worse the salinisation of the soil. Again, the more fallow land there is (that is, the lower the cropping intensity) the greater problem there is with soil salinisation because water is moving up, whereas in adequately irrigated cropped land it is moving down.

FIGURE 11



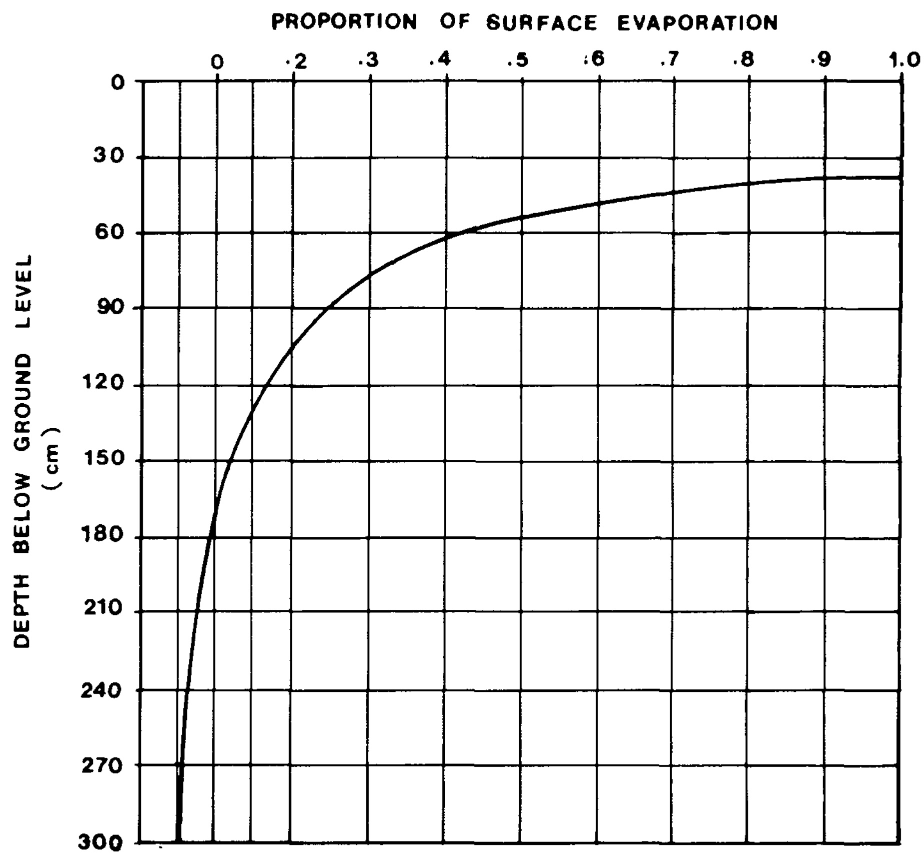
Research work into the behaviour of crops under high watertable conditions is still very much neglected. This is all the more surprising because field observations are very easy to make whereas, by contrast, the controlled experiment is notoriously difficult. Still among the best work is the series of field observations made in a single season on the Lower Indus Project. These are illustrated in the diagram below (Figure 12), for wheat which illustrates the principles stated earlier. This work was done by placing boreholes in wheat fields, measuring the watertable depth and taking samples of the upper groundwater for laboratory analysis. Later at harvest time crop samples were cut for yield determination.

FIGURE 12



For fallow land the manner in which evaporation changes with the depth to watertable is the important factor as this controls the rate of soil profile salinisation. Again, from the same source for a silt-loam soil the following figure was derived.

FIGURE 13



As can be seen, the evaporation from 25 cm deep or less is equal to evaporation from surface water. This diagram would be entirely different for the varying soil types and, as yet, there is inadequate research into the matter.

There may be advantages in using tubewells to drain watertable down even further than is strictly required for drainage alone, especially if this fits in with a re-use pattern. It may be better to drawdown in winter, say, in anticipation of increased irrigation applications in the summer, thus minimising the installed capacity required. Alternatively, close to a large river that is connected to the watertable, it may be feasible to drawdown substantially in the low flow season (and to use the pumpage for irrigation) and allow recharge to take place in the flood season. Effectively this involves using the aquifer as a storage reservoir.

A temporary rise in watertable after a storm (say, for a week) may be harmless if groundwater is fresh, but disastrous if it is saline. Hence a temporary drawdown to protect a crop from seasonal flooding would have to be deeper if the groundwater was saline. Economic depths for such protection are empirical matters not yet investigated.

The upshot of this digression is that the optimum depth at which to establish the watertable is an essentially economic decision. What crops are to be grown? What is the maximum intensity that can be sustained? What is the cost of the drainage effort required?

If, for example, the watertable is to be established at, say, two metres, then tile or open drainage would be prohibitively expensive. It is in this case that tubewells can be used very effectively for drainage provided that there is a suitable aquifer which is hydraulically connected to the watertable. If the groundwater is saline, then it must be disposed of through surface drains or skillfully mixed with surface water but, if it is reasonably fresh, there is the added bonus that it can be used for irrigation, and the benefits become very large. The watertable can be controlled at virtually any level by wells if there is sufficient installed capacity, merely by increasing or decreasing the amount of pumpage. The system can be made to work with low intensities whereas, with conventional drainage systems, the fallow land associated with low intensities will almost certainly become saline. However, once the cultivated and fallow land is drained by tubewells, the economic return to additional water and to high cropping intensities is likely to be high.

Virtually the only comprehensive project, in the developing countries, which has wells for drainage alone, for drainage and irrigation and, where water is of marginal quality, for drainage and irrigation often mixing with surface water, is the Khairpur Project in Pakistan. This project worked very well initially, but after about ten years it is now suffering from inadequate maintenance and indifferent operation. Certainly this is a project that would repay a thorough ex-post evaluation.

One consideration which must be taken into account in favour of tile drainage is that, with high intensities and adequate irrigation applications, the upper groundwater should improve in quality so that the drainage water can be re-used for irrigation. This can go on indefinitely provided that there is a net export of salt.

Summarising, when tubewell drainage works, it is generally cheaper and more flexible than any other means and, where the pumped water is fresh, there are vast benefits available if it can be used for irrigation. The chances of a tubewell scheme being maintained are probably slightly better than for open drains. There are fundamental economic decisions to be made in establishing the best operational depth at which the watertable should be established.

4. GROUNDWATER AND INCOME DISTRIBUTION

4.1 Groundwater as a Common Property Resource

Underground fresh water, like common grazing land and sea, river and lake fisheries, is a potentially productive resource with open public access. Groundwater potential has rarely been fully developed in low income countries. Indeed it is estimated that in Asia more than 50 million farmers, with only one hectare or less of land, live on farms with undeveloped fresh water within two metres of the surface (IDS 1980). However, at the other extreme, there is a growing realisation that there are now a number of areas where over-exploitation is likely or has already resulted in either falling watertables or saline water intrusion into fresh groundwater aquifers, or both. In India the National Irrigation Commission (1972) estimated that only 30% of national groundwater potential was being used. On a state basis, progress varied from over-exploitation in Rajastan, close to optimum exploitation in Haryana, Madras and Pondicherry and Punjab to very little development in Assam, Bihar, Jammu and Kashmir, Orrisa and West Bengal.

Open access to exploitable communal resources without public control means eventually losses for all involved, whether it is in the form of less or more costly irrigation and drinking water from underground, overgrazing and soil erosion of communal pastures, or less fish at higher average cost from surface water sources. Common property resources require public control if economic efficiency is to result from their development. The more profitable the resource exploitation to private developers the more urgent is the need for effective public control. For the most part groundwater development is extremely profitable.

Open access can be a misleading term as the landless are clearly excluded. Even those with land need capital investment to obtain access. Low income farmers are effectively excluded from communal or common property resources if they lack the complementary resources to use them. To benefit from groundwater, grazing or fish stocks, a farmer needs land and respectively water lifting devices, livestock and fishing equipment. If a public policy objective is to include the sharing of benefits from use of common property resources by those living in poverty, then the poor must first secure access to the resource, and then the means to exploit it. In principle, an alternative means of redistributing the benefits from natural resources, such as groundwater, is to tax the net benefits of those with access and transfer this revenue to the poor by other means. In poor countries the record of such fiscal policies is not generally good. Even where the incomes of the poverty group have been increased in absolute terms, the level of increase is often unsatisfactory and income disparities within society may still widen.

4.2 The Distribution Dilemma

To ensure optimum groundwater development in low-income countries, the public authorities thus face two separate but related and possibly conflicting tasks. First, groundwater development, in most cases, must be subject to overall, normally public, control to obtain maximum return from its use. Secondly, if public policy includes distribution objectives, public intervention will be required to obtain a fair allocation of groundwater resources. Even the first task is generally difficult to achieve in the circumstances existing in most countries. It requires a legitimate public interest in what are often legally private rights. Furthermore, public authorities must derive a consistent set of criteria for various components of the well and wellfield design and operation, and exhibit a determination to apply them. For example, criteria relating to the optimum rate of water mining or optimum depth for groundwater stabilisation need to be set and applied in congruity with other criteria without fear or favour.

The second distribution task presents an even more formidable undertaking. Indeed, some observers consider it a vain exploration. It is sometimes argued that, to search for technological solutions to problems of, say, gross income, inequality is not simply a vain exploration but that it is misconceived because technology itself is the cause of the problem. For example, Falkenmark et al. (1980), discussing water development, argue "it is an increasingly recognised fact that the introduction of any technical improvement immediately widens the gap between rich and poor, whether it is in water supplies, tubewells or irrigation credits". The problem may be more apparent than real if the gains are such that the poor are relatively worse-off but absolutely less poor.

It is apparently a 'fact' that technology causes the problem of an increased gap between rich (less poor) and poor. For those steeped with the Baconian regard for facts, it is therefore tempting to conclude from this that, to prevent the problems of inequality, new technology should not be accepted. It would appear that the Luddites were ahead of their time. Machines not only take away jobs but they cause increased income inequality. We do not consider that this statement is empirically true nor the inevitable consequence of technological change. Certainly new technology always appears to threaten increased inequality, but the effect in the long term is either to diminish inequality or to so raise base incomes as to make any increase in inequality somewhat more palatable. Many researchers in this field have neglected the real benefits from increased income of the poverty group in absolute terms and the impact of levelling mechanisms within society which prevent excessive concentration of economic power.

Practical experience, or at least the authors' interpretation of recent published material, suggests that it is easier to obtain a modicum of wealth or income redistribution when incomes are growing and when new resources or opportunities arise that are not yet the charge of a particular group. Groundwater development is generally profitable but monopoly control of the limited supplies can rapidly arise once this profitability is demonstrated.

The potential for a permanent monopoly distinguishes groundwater from other areas of technology. In the early years of the seed/fertiliser revolution it was common for large farmers to be far ahead in adoption, but for this to be but a temporary phenomenon with smaller, poorer farmers adopting after a time-lag. Similarly (but for different reasons) tubewell adoption was first and foremost with the large farmer group. However, given a limited supply, early monopoly control of groundwater can become an irreversible and permanent feature.

In the light of experience in other areas of rural development, it is possible to argue that the potential gains from public control, pursued for either efficiency or equity reasons, can be largely illusory. Any prospectus neglects the inefficiencies and costs of imposing more responsibility upon the already over-burdened bureaucratic administrative process. Here one is dealing with aspects of political economy and therefore political values must influence judgement and choice. As examples one can take virtually any of the many well intentioned land reform programmes.

4.3 A Resource for Poor Farmers?

Groundwater also presents particularly intractable and essentially technical problems for those favouring bureaucratic allocation. These are set out more fully later. In principle there is a good case for public initiatives where, for example, groundwater is undeveloped or the pace of development is slow; where the collective task of drainage is to be achieved; where externalities in the form of excessive pumping threaten to increase new investment costs, marginal pumping costs, or cause saltwater intrusion into fresh groundwater aquifers. However, control of over-investment in wells is often virtually impossible. For example, in Cyprus and Jordan the public authorities have not been able to control either drilling or subsequent pumping. In Cyprus an independent politically powerful group of relatively small farmers act with considerable independence (Republic of Cyprus 1980) but in Jordan it is a relatively small group of very large farmers (and politicians) who defy the drilling and withdrawal regulations (Clayton et at. 1974). In fact the most important task of control of subsequent withdrawals from private wells has proved absolutely impracticable in almost all circumstances. Nevertheless, in the search for fresh approaches to remove or alleviate the worst aspects of abject rural poverty, some writers have examined the groundwater potential as it is a widely available, largely under-exploited resource with a special high potential for profitably increasing agricultural production. For example, the report of a recent IDS Study Seminar* concluded enthusiastically:

> "Groundwater resources may be the largest remaining untapped resource available for alleviating the pervasive and intractable problem of rural poverty in South Asia. Groundwater is at present being appropriated largely by those who are richer (or perhaps more accurately less poor) and more powerful. Opportunities for those who are poorer and weaker to benefit are passing. Who is to gain from this last frontier? The haves or the have-nots?"
>
> "Groundwater development and lift irrigation offer a massively under-exploited resource and opportunity. In India, less than half the safe yield of aquifers is currently used. In Bangladesh, a country sited on one of the largest and richest aquifers in the world, only one sixth of the potential is being tapped. Groundwater is a last frontier. Intensively used, it has potential in India and Bangladesh for the direct creation of additional livelihoods for at least 50 million families. In addition, there are opportunities for lowlift pump developments from surface water sources, particularly in Bangladesh.

Footnote : * IDS Study Seminar 88 (1980). Who gets a last resource? The potential and challenge of lift irrigation for the rural poor. Discussion Paper 156, Institute for Development Studies, University of Sussex. One author (I.D. Carruthers) was a member of the drafting group and this section draws on the text with permission.

Few, if any, areas of technology and investment can rival groundwater and unutilised surface water in this potential for productive employment. However, an appropriate share of this last frontier will not be taken by those whose need is greatest without positive policies to secure their interest."

"New groundwater exploitation presents Governments with unusual room for manoeuvre in choosing social and economic policies. However, groundwater is only part of the rural social and production system. Its development can contribute to the alleviation of poverty but it is no panacea. Its potential contribution will only be maximised if supporting policies are implemented. In this sense, groundwater development should be viewed as a complement to, not a substitute for, the implementation of land reform."

"The main immediate opportunity lies in shifting the benefits of lift irrigation development more towards smaller farmers and landless labourers. In many but not all respects the interests of these two groups coincide. Some mechanical farming innovations require resources which, in the developing countries, virtually exclude small farmers and agricultural labourers from obtaining or using them; and the record of co-operative ownership and management has been dismal. In lift irrigation, the technical factors which in the developing countries have confined manufacture of diesel and electric pumps to 3 to 5 and higher horsepower sizes have, at the same time, demanded larger farms for economic use and have excluded the smaller poorer farmers from participation. The opportunity now is two-fold. First, it is to improve traditional lift irrigation devices and distribution systems. These are typically locally made and maintained, rely predominantly on human and animal energy sources, and, although already relatively cheap and effective, could often be made more efficient with comparatively modest research inputs. Recent work, for example, shows that substantial improvements should be possible in the performance of the dhone which currently accounts for a little less than a half of the total irrigated area in Bangladesh; and if similar breakthroughs could be achieved with the indigenous methods currently used in some two-thirds of India's 6 million open wells, then the pay-offs in terms of increased output and reduced drudgery are potentially very large. Second, there are opportunities for developing and improving new small-scale technology specially designed for small farmers. Such technology includes both hand- and bicycle-powered pumps, relying on human energy; and solar-powered micro-pumping units, designed specifically for the very small farmer, might in future prove economic, although currently available technology is only viable on holdings of 2 hectares or more*'.

If we examine the experiences of groundwater development, it is hard to understand such optimism. In fact the general experience of public policy in devising and administering income redistribution policies can be considered

Footnote : * A UNDP financed study by Sir W. Halcrow & Partners is presently evaluating field performance of small solar-powered pumping devices. In discussion with F. Hotes of the World Bank it was stated that solar powered pumps are not viable at any size yet.

poor. It is surely obvious that it is naive and unrealistic to assume that, providing an economically sound and just development policy can be derived, it can and will be carried out.

We would argue that groundwater programmes are likely to be a relatively unsuccessful area for income redistribution policies. This judgement stems from observation of public and private developments in several countries and a consideration of technical, economic and social aspects of the technology. It is difficult to regulate any rural investment but installation and operation of tubewells proves particularly troublesome. On one 20 ha pilot project in Indonesia five tubewells remained undetected by a monitoring team for several months. Tubewells are most likely to be an asset of the large, rich farmer for they require 'lumpy' capital investment; there are potential and, given subsidised credit, fuel and so forth, actual economies of scale; the crops have a ready cash market; and, given unreliable fuel and spares supply, there is a relatively high risk. There is a technical potential for local monopoly. High profits from well operations, threats to land ownership from reform policies, corrupt use of public funds and influence in such matters of well siting can all be readily found in rural areas and give credence to our view. As an area of in-depth sociological study it deserves priority.

This is clearly illustrated by experience from India. In West Bengal, despite a Government committed to aid the poorest, social relationships in rural areas are still dominated by feudal categories such as 'landlord', 'usury-lord', 'speculative trading-lord', 'caste-lord' - to which T.K. Banerjee (private communication) adds a new category of 'water-lord', a term also commonly applied in Bangladesh. He explains that land holdings are highly fragmented and thus even the smallest tubewell with command over a mere three hectares contains land belonging to several families. Thus, when a farmer installs his own tubewell, he will have access to a fraction of the command. However, because of the level of groundwater availability and the local drawdown his well causes, he will have technological control of the irrigation of land of the surrounding farmers. By virtue of his local monopoly he can dictate terms to supply irrigation water. This may take the form of high cash payments or, increasingly, a new form of share-cropping in the form of either a proportion of the land on nominal rent or a share of the crop. Alternatively, the lessee may then work as a wage labourer for the water-lord. This would be a voluntary contract but possibly one made feasible by a subsidised state credit for the original well.

Dr. Banerjee highlighted the role of credit in this process with reference to the programme of the Indian Agricultural Refinance and Development Corporation (ARDC). Interestingly not one of seven in-house evaluation reports examined of the ARDC programme in this and other States mentioned these factors. They stressed repayment rates (13 to 70%), speed of loan sanction, and implementation (generally good), cost of wells and other technical problems. A World Bank project performance audit report of the same projects pays considerable attention to the problems of rapid development, technical efficient use and access of low income farmers to groundwater. These are general problems and are discussed here in some detail.

Existing credit facilities are a constraint to tubewell development. Many small farmers (say less than 2 ha), who could economically use a tubewell, either individually or as a member of a co-operative group, find a deficiency of medium term credit to finance original installation. The volume of medium term (not short term) credit is inadequate for their needs. In addition, the problem of providing collateral where land is the main form excludes small farmers and share tenants.

In India the cropping intensity and standard of crop husbandry on private tubewell irrigated farms exceeds that on all other units of agricultural production. One of the most effective ways in which small farmers can increase their productivity and income is by a shift to more multiple cropping. Singh (1979) argues that the most necessary conditions in order of importance for bringing this about are:-

(i) increased irrigation and better water control;

(ii) improved quick-maturing crop varieties;

(iii) improved crop management;

(iv) increased nutrient use;

(v) better insect and disease control; and

(vi) more efficient post-harvest technologies.

He argues that increased irrigation is central and that the main constraints for private groundwater development are inadequate investment funds and medium term credit, fragmented holdings with small scattered parcels, no satisfactory small scale technology and, for public wells, the lack of farmer control over distribution.

4.4 Aquifer Management Constraints

Additional wells, which are sunk in an area where at present all recharge is pumped, will, when operated, threaten the technical efficiency of the original wells and impose financial penalties in the form of increased pumping costs. The dilemma is how to protect the asset of an early investor and, if no mining is contemplated, how to pump groundwater at lowest average cost, yet, at the same time determine how to spread the benefits to those by-passed in the first phase of development. This dilemma is compounded in that the early developers are generally the larger landowners or the richer farmers, and thus their success with groundwater development perpetuates and exacerbates economic and social divisions within the rural economy.

New technology can lower long-run average costs but create short term social problems. For example, imagine a valley with groundwater extracted from a large number of open wells using wind power. This system had evolved over several decades and extraction, though insufficient for all the land, is in balance with recharge. Excessive withdrawal by one farm, to a certain extent, is limited by the technology in that there are no economies of scale in wind pumping, and farmers must replicate facilities to obtain additional water. If one farmer disturbs the equilibrium by purchasing a diesel powered pump and finds that he can economically irrigate all his farm, two things will happen. First, farmers in the immediate vicinity may be subjected to a declining well yield and may be forced either to purchase similar technology or to give up irrigation. Secondly, more distant farmers may observe the original innovation, copy the example and very rapidly all the valley's groundwater could be exploited by, say, one tenth of the previous wells. Given economies of scale and high investment costs, the new technology could be controlled by a few of the richer or larger farmers with predictable social consequences.

This new technology might not lower the average costs of water pumped. Farmers purchase equipment to increase their supply not simply to lower costs. If foreign exchange has high social opportunity cost, then, unless appropriate pricing of pumps and fuel are made, there will also be an element of public subsidy. Once the diesel capacity is installed and farmers can obtain water at relatively low marginal pumping cost, the scene is set for overpumping of the aquifer and gradual increases in the cost of all water pumped as the watertable declines.

This hypothetical example of a shift from a balanced appropriate wind power technology to an unsustainable high cost system is all too commonly found where unrestricted private development has occurred. Nevertheless, this does not imply that appropriate technology should be subject to preservation orders. But, in considering interdependent surface and groundwater systems, the complexities of the system have to be recognised and the social and political linkages incorporated in decision models.

It is questionable whether any significant change in the distribution of power in rural areas can be achieved by bureaucratic administration of any technology. Experience with other forms of technology, such as farm power, suggests that government authority in this area is extremely limited. Economic, social, religious, political, even police and military power rests essentially in the same hands. This raises a number of questions. If such a situation is a general feature of society, is it not unwise to try to resist this general problem with a limited number of weapons, let alone the one weapon of groundwater? On the other hand, is groundwater special in the sense that it is, as the Sussex group suggests, a last opportunity to allocate a publically controllable (although normally privately owned) resource which is not yet fully exploited? Is it worth taking a stand at this time for the benefit of low income groups which would not be contemplated for, say, land because the problem is being tackled relatively early and public precendents are therefore more acceptable. Whether public intervention is promoted for increased efficiency or equity grounds, there are various policy instruments available.

To protect their investment in an individual well, the financing authorities have sometimes specified minimum well spacing. In India, for the most part, this does not appear to have been necessary because no major interference between wells has been noticed. Over much of India recharge either exceeds present withdrawals or, in hard rock areas, aquifers are not connected. Where a risk of interference existed, the spacing criteria recommended by credit agencies were extremely conservative. Furthermore, farmers have to date used their own discretion and have been reluctant to place wells adjacent to existing wells. Whether this situation is liable to continue is uncertain. In the long run control by spacing seems unlikely to succeed by itself. Wells have certainly been sunk in some areas within the specified zone of an existing well. However, where over-development of an aquifer has occurred, this is commonly, but probably erroneously, attributed to the abnormal drought in 1977 to 1979 rather than to installation and use of excessive pumping capacity.

What is required when groundwater development options are being assessed is careful appraisal of a wide range of alternative policies including their impact upon various rural interest groups. Table 1 shows a comprehensive range considered for farms on the over-developed aquifers in Coimbatore, India.

The overdraft problem, such as exists in Coimbatore, can be expected to grow. For ten years in India model groundwater legislation has been available but it has not been enacted and there are no effective legal controls to well sinking. An individual farmer will normally gain more than his private costs by sinking and pumping a well but, once all recharge is being pumped, any additional exploitation will cause the watertable to fall and impose additional (social) pumping costs on all recharge pumped. As with the problem of common land grazing, the private gains of over-use exceed the private costs, although the social costs exceed the social gains. Over-grazed common lands and depleted or quality damaged groundwater reservoirs are economic analogues, (some writers argue that, by strict definition, groundwater is not a common property resource, or an open access resource, but a 'fugutive' resource. It is only owned when captured).

A simple water budget can show that overpumping is likely to occur when only a small proportion of the land is irrigated. In large parts of India annual recharge is less than 100 000 m^3/km^2 and, with an average farm size of, say, 2.5 hectares, this would give only 2 500 m^3 of recharge per farmer. This is sufficient to irrigate only 0.4 ha or one-sixth of the farm. It is certainly an uneconomic level of withdrawal to justify any one farmer's investment in a tubewell. If only five farmers in each square kilometre have fully irrigated their land, then all the groundwater potential is committed.

This example illustrates two vital points. Firstly , in such conditions, if all farmers are to share in an economic exploitation of groundwater, then some form of co-operative or government owned and operated rationing facilities are essential. The field operating record of such ventures does not give cause for great optimism. Secondly, if groundwater abstraction rights are to be allocated on a first come, first served or prior right allocative principle, then operation of this profitable investment will be confined for all time to the early adopters who are, in practice, the richer farmers.

The role of minimum spacing and/or density regulation through legislation, credit control or other administrative devices, such as allocation of electricity connections or diesel fuel rations, merely reinforces existing income distribution patterns. Absence of control will lead eventually to excessive pumping. Thus devices designed to bring about technical efficiency are, in fact, effective in strengthening the position of a richer minority group. The injustice of these indirect effects is compounded, if the credit is subsidised, if it is not repaid in part or in full, if electricity or fuel oil prices are below social costs, or if rationed resources are not directed to the highest social opportunity cost activity.

4.5 Legal Restraints to Redistribution

In countries where a common law approach is followed, absolute ownership of land and unrestricted use of its subsurface resources on that land is accepted,

TABLE 1

Policy Options for Improved Groundwater Development in Coimbatore

Option	Who gains (+)? Who loses (-)?			Feasibility	
	Rich farmers	Small farmers	Landless labourers	Financial	Political
1. Exploit deep water (300 m)	++	O or +	+	?	++
2. Inter-basin transfers (from Kerala)	++	+	+	?	-
3. New irrigation projects	++	+	+	?	+
4. Reduce water loss (line channels, drip, sprinkler)	++	?	+	+	++
5. Water conservation (bunding, recycling, artificial recharge)	+	+ or -	+	+	+
6. Lift technologies for small farmers (create new ones; use existing subsidies)	+	++	+	?	
7. Allocate new wells to small farmers	--	++	+		--
8. Desilt, deepen, drill 'in-well' in open wells	++	+	?	?	+
9. Control density of wells	+	- - or +	-	++	+
10. Ration electricity	+ -	+ -	++ -	+	-
11. Two-part electricity tariff (higher not lower charges above a certain level of consumption)	-	++	-	+	?
12. Alternative farming systems					
- irrigated	+	++?	+	?	?
- dry land	-	+	+	?	?
13. Regulate crops permitted (paddy, sugar cane, etc.)	?	?	+	?	-
14. Nationalise groundwater	-	?	+	?	?
15. Tax groundwater (tradeable ground-water quotas)	-	+		+	-
16. Alternative user organisations (co-ops etc.)	-	++	+	-	-
17. Alternatives outside agriculture	--	?	++		
18. Subsidise migration of the poor to 'growth' areas			?-		
19. Eliminate credit and other public subsidies	--	-	?+	+	-
20. Agrarian reform	-	+	++	-	-
21. Mine groundwater	++	-	+?-	+-	+
22. Do nothing	++	-	?-	+	+

From working paper at IDS Study Seminar 88, 1979.

provided that there is no malicious use or unnecessary waste. Under English common law system, which is the legal basis still widely followed in some developing countries, sale of water is not permitted. When water is short, courts will apportion water in line with reasonable use, often taking account of the character of use (for example, drinking water before crop water) and the length of time for which use has been established. In arid areas (for example, Western States of America) this apportionment system and restriction on sale of water has been modified and an appropriation doctrine adopted with 'first in time, first in right' but with no barriers to new wells. Many of the former British colonial territories now operate under an appropriation doctrine which protects in a permanent way the early developer and allows sale of water. These legal institutions create rigidities in allocation or rights to use, which may preclude public action to promote both efficient use of groundwater and integration with surface resources and also accommodating the needs of small farmers who are late developers.

In California a system of correlative rights has evolved which has several attractive features which make it worth examining for application in developing countries (Veerman 1978). Under this system "owners of all lands that overlie a common supply of percolating groundwater have correlative and co-equal rights to the reasonable beneficial use of the water of that supply on, or in connection with, their overlying lands". Furthermore, in the event that the demand for groundwater based on co-equal rights exceeds the supply and therefore some form of rationing among the overlying landowners is necessary, the water may be apportioned by court decree (adjudication) among them in accordance with their respective reasonable beneficial needs and in proportion to their historical use as a residual element from the appropriation doctrine. However, it is the entitlement of all land owners to a reasonable share of scarce water which is the important principle. Furthermore, it is a principle which could be applied without nationalisation of groundwater and it can be applied by neutral courts, if they exist and if all have equal access, only when needed, thereby obviating the need for a bureaucratic licensing and regulatory agency for all wells, until absolutely necessary.

There is an urgent need for research to devise appropriate legal frameworks to fit various social and political systems in advance of the period when integrated water development is essential (see Hutchins 1964 for a review of US experience). It is evident that in many countries the trends in groundwater development are leading to lost opportunities, and problems and inefficiencies with which the existing water institutions are unable to cope. The regulation and management problems that are emerging require new and more effective water institutions if the groundwater development momentum is to be maintained.

The State of Arizona, in its 1980 Arizona Groundwater Management Act, has provided a legal framework to help both conserve and manage an over-exploited groundwater resource. It provides an imaginative, indeed an exciting, prospect of controlling what appeared to be an intractable groundwater overdraft problem. The State presently consumes nearly twice the annual supply of groundwater and, in consequence, the watertable falls 2 to 3 m per year. Imported surface sources cannot make good this deficit; hence the Act aims to provide a comprehensive framework for management and regulation of the withdrawal, transportation, use, conservation and conveyance rights to the use of groundwater. James Johnson (1980) provides a clear comprehensive summary of the Act in what is essentially non-legal language. Areas of the State are designated Active Management Areas and detailed aquifer management plans are prepared to be implemented over five phases to the year 2025 when withdrawals should reach safe yield. The mechanism is public control over well investment and pumping and public powers to purchase established irrigation rights (called rather quaintly 'grandfathered' rights). These rights to withdraw water will be purchased by the State using funds from a withdrawal or pump tax. This tax will be used to pay augmentation works (surface water imports, artificial recharge schemes, etcetera) and to buy and permanently retire irrigation land with 'grandfathered' withdrawal rights.

5. PUBLIC VERSUS PRIVATE DEVELOPMENT

Any discussion of recent experience and an assessment of potential groundwater developments must fully consider the pros and cons of private and public development and the likely merit of various forms of joint initiatives. The system that is most appropriate varies with the technical, administrative and political circumstances in the country concerned. Nevertheless some generalisations are possible. There are five areas where, legal powers allowing, public initiatives might be favourably considered :-

(i) for pioneer development;
(ii) for poverty alleviation;
(iii) for technological advantage;
(iv) for management system efficiency;
(v) to realise aid opportunities.

5.1 Pioneer Phase

In the pioneer phase the common sequence of events is that one or more innovative farmers sink shallow wells which demonstrate the technical feasibility of groundwater development. Initial interest can sometimes be stimulated by public pilot projects where the wells and channels are installed, and initially operated and maintained, by a public authority. At this stage water is normally supplied free on demand to the farmers. This is being done in Indonesia where it is hoped, with the additional water, to raise three crops a year instead of the present maximum of two. Once the extent and quality of the water and the technical feasibility of pumping is established a large public project is frequently planned. This may be for a settlement scheme (Wadi Dhuleil and other projects in Jordan - Clayton et al. 1974), perhaps for drainage (Khairpur, Pakistan), perhaps to augment unreliable rainfall or unreliable surface irrigation supplies (Bangladesh Deep Tubewell Projects), or perhaps to extend the irrigation season (Kediri-Nganjuk, Indonesia). The demonstrable effect of these pioneer wells can lead to extremely rapid private development of groundwater. Uncontrolled private development has its dangers but there is no doubt that, once momentum is achieved, it is considerably quicker than public exploitation. In the Punjab Province of Pakistan some 9 000 wells have been installed by the public sector compared with some 120 000 by private farmers. However, it is true to say in this case that it was probably the public development that sparked off the private sector.

5.2 Poverty Alleviation

The use of public initiatives in the groundwater sector for poverty alleviation programmes has already been discussed. It is sufficient to note here that public monopoly or a degree of public participation may be desirable where all or some farmers are too poor* to invest in, or even to maintain, private facilities and where fairness or equity goals dictate a rationing of scarce supplies. In areas

Footnote: * It is well known that despite studies showing that poor farmers have no 'repayment capacity' they do in fact have to pay the operators who in turn pay other officials. Corruption is so widespread and entrenched in some countries that it may be wise to take it into account rather than to ignore it.

where the early development of groundwater was by private farmers, a continuation, or even a reinforcement, of the existing inequitable allocation are not ever likely to be politically acceptable. Controls on withdrawals, which would require the setting, monitoring and reinforcement of abstraction quotas for each private well, are in principle a fair method of allocating scarce supplies. However, the detailed mechanisms for enforcing quotas are, as yet, undefined and the practicability of operating them is extremely vague.

Extensive experience with the much simpler task of controlling allocations of surface canal irrigation water according to pre-determined schedules does not give cause for much optimism regarding successful operation of groundwater withdrawal quotas.

Public groundwater developments can create opportunities for reform of surface irrigation allocation. For example, in a situation where, over a long period, farmers at the head of canals or watercourses have taken an undue share of surface resources, reform and reallocation in line with original design may be impossible without additional water at peak periods. The advent of public wells discharging into canals or watercourses can create extremely favourable conditions for enforcing equitable allocation rules. Such an opportunity can be strengthened by strategically locating wells where needs are greatest.

5.3 Technological Opportunities

Several essentially technological advantages or even imperatives can be claimed to support public initiatives. Where groundwater is saline and is pumped, for drainage purposes, to be disposed of in rivers or mixed with fresh surface water in canals, no private group is likely to be effective. In Britain and other industrialised countries with large farms and profitable farming systems, it is found that drainage co-operatives do flourish with a certain amount of Government regulation and financial support, but this experience has limited relevance in low income countries.

Public enterprise is desirable in other intractable development conditions, such as where the risk of a dry well is high (high risk needs defining in relation to farm size, farm income, well investment costs and so forth), where there is a risk of saline water intrusion from underlying aquifers or lateral encroachment such as that from the sea, where the aquifer is overlain with hard rock or is too deep for farmers to bear the high initial costs of drilling, or where some desalinisation is justified. In such circumstances there is need for various degrees of public investment and operation. The precise form and extent of public involvement is, of course, to a large degree a political as well as a technical issue.

Further potential technological advantages can accrue to public investment where economies of scale exist in well construction. For example, in the very deep high quality aquifers of the Indo-Gangetic Plain the unit cost per cubic metre water lifted falls over a wide range, often up to very large wells pumping at a maximum around 150 l/s. The shallow low discharge well installed by small farmers typically discharges about 25 to 50 l/s. Other things being equal, an increase in screen length lowers drawdown and an increase in screen diameter reduces pipe losses (Stoner, Milne and Lund 1979). These investments will increase capital costs but reduce operating costs. In most cases, with discount rates in the 10 to 15% range, minimum present value of costs per unit of water pumped are well outside the range of small private wells. Indeed, the economic optimum capacity well is often larger than that installed in public well programmes. There are various explanations for not selecting the apparent optimum, including the relative flatness of the present value of the total cost curve close to the optimum which means that there are fairly wide design limits within which overall costs change insignificantly.

The possibility of manipulating design parameters, such as screen length, well diameter and design discharge, and thereby changing the balance between capital and recurrent costs in the total cost, can be important when the incidence of cost is considered. In a situation where public investment resources are scarce, where the recurrent budget is under severe pressure but where operation and maintenance costs are borne by users, Governments will be rational if they encourage private investment, or failing that, if they economise on investment with shallow wells, narrow diameters and so forth. This latter tactic will be all the more likely if there is zero or very small economic penalty in doing so. On the other hand, where soft-term aid resources are available for capital but not recurrent expenditure, for imported items but not local costs, the public authority may be sensible to look more favourably upon imported capital-intensive solutions which save on the recurrent expenditure. Although aid donors, for their part, are aware of the local cost and recurrent cost dilemmas, to date there has been inadequate response if actual disbursement patterns are examined.

Where no aid is available and public finance has high opportunity cost, Governments may be prepared to see and encourage private development, to mobilise domestic resources, even if it is considered technically inefficient with considerably higher cost per unit of water.

Technological opportunities such as economies of scale often prove difficult to realise. For example, problems of location of public wells have been reported. In Bangladesh there are examples of larger farmers and political leaders corruptly influencing well location for their private advantage and in the process selecting unsuitable sites (see, for example, Hamid et al. 1978). The easily regulated alternative of the locating of public wells strictly on a grid basis, as was undertaken in Khairpur and elsewhere in Pakistan which minimises electrification costs and interference between wells during pumping, has offsetting disadvantages. A grid location is extremely unlikely to suit topographical and farm management needs and the trade-off of design versus farm efficiency needs to be carefully assessed in the light of social and political realities.

5.4 Management System Efficiency

As water resource developments approach maturity, the benefits to be derived from a fully integrated system increase in importance. For example, these circumstances inevitably occur where there is the possibility of conjunctive use of groundwater with surface water but, in addition, integrated management is important where surface reservoirs are operated for both hydro-electricity and irrigation; where groundwater has to be protected for drinking water use; where very cheap off-peak electricity can be used for groundwater pumping and where groundwater mining threatens to impose various social costs. In such conditions overall public management or at least regulation is desirable.

In many developing countries the pioneer water development phase is over and the opportunity and need for conjunctive management of all water resources is now incontestable. Private control of groundwater can impede this process.

Further formidable institutional barriers to effective implementation remain within the public sector. There has been a de-emphasis on public tubewells in the India IV and V Plans because of disappointing experience in installation and operation. One of the main constraints to integrated management is the multiplicity of agencies which are involved in the water sector, each with its own narrow objectives. Obtaining an agreed policy, then monitoring and regulating diverse public and private water using enterprises in rural areas are often intractable impediments to progress in integrated water management. Examples of the lack of active co-operation between involved agencies are numerous and to cite one or two would be invidious. The most obvious problems arise when surface irrigation is within one ministry or agency, groundwater irrigation within a second and rural and urban drinking water in a third. All too often competition for funds, personnel and status are more evident than co-operation.

Where excessive fragmentation of farms exist, public initiatives may be necessary to ensure development of groundwater. Fragmentation of farms into several parcels impedes effective private well development. In India farms over one hectare have 6 to 9.4 parcels per farm depending upon farm size. Smaller farms have fewer parcels but even the 0.2 ha farms have nearly two parcels per farm (Srinivasan and Bardhan 1974). Clearly most parcels are below the minimum size for a tubewell and therefore economic success will depend upon co-operation among farmers (Dhawan 1977b). To the extent that parcel size is correlated with farm size (for example, 0.2 ha farms have average parcel sizes of 0.1 ha, 2 to 3 ha have average parcel sizes of 0.35 ha, 10 to 12 ha have average parcel sizes of 3.3 ha) the small farmer has a bigger problem than the larger farmer. Singh (1979) reports a similar position exists in Pakistan and Bangladesh.

5.5 Aid Terms

It has already been noted that aid terms can favour both public investment and capital intensive designs which, from an overall perspective, might be considered more appropriate. Designs are likely to be produced in line with anticipated donor agency preferences. Until and unless further flexibility with regard to local cost support and recurrent budget support is forthcoming from aid agencies, the situation will not change (Carruthers 1981). Indeed, whilst industrialised countries are in an extended recession, it is unlikely that aid terms will favour a shift to more appropriate technology. In the face of differential inflation on global energy costs it is far from certain that a shift to apparently more appropriate cheaper local technology is desirable in the long run, if it increases the energy requirement for pumping a unit volume of water.

5.6 Advantages of Private Development

The major proportion of groundwater investment in the 1970s came from private farmers, for the most part using non-public sources of funds. Private development, once it is demonstrated to be privately profitable, is more rapid than public development. There can be no doubt that the individually owned private tubewells and pumpsets played a major part in the Green Revolution - more correctly termed the wheat revolution, in India and Pakistan (Pearse 1980). Private well owners maintain their equipment in good order and have high operating efficiency. Private well owners have mobilised savings which might otherwise lie dormant or be used on wasteful consumption.

However, the extent and rapidity of installation of private wells can lead to excessive levels of investment. This is spectacularly illustrated in south-east Cyprus where the good soil areas are criss-crossed by distribution pipes, the watertable is falling and harmful saline intrusion is occurring. When water levels have declined to uneconomic levels, extraordinarily expensive actions have sometimes been taken. There are several instances where the Cypriot farmers have removed soil to a depth of one metre and transported it to places where groundwater was undeveloped and left the original fields derelict.

The extent of over-investment, which can occur, was shown by Gotsh and Yusuj (1974) when they compared linear programming models for Punjab farms using integer and normal linear programming assumptions. Their programming models indicated that a relatively large 15 acre (6 ha) farm required only 10% of the capacity of a tubewell for optimum use. However, field examples of 10 farmers sharing a well or of one farmer selling water to 10 others to obtain optimum utilisation are rarely, if ever, found. Most 15 acre farmers with a tubewell have very low rates of tubewell use. This may well be privately profitable but from a social view point there is over-investment in tubewells.

Although uncontrolled public groundwater exploitations can lead to excessive levels of investment and wasteful or even harmful pumping patterns, this risk can easily be over-emphasised. Furthermore, there is always the temptation to compare a situation of excessive levels of private investment, where there are many low income farmers excluded from access to the resource, to a Utopian perception of a public scheme with optimum levels of investment, optimum operating policy and public access. Such argument is not confined to advocates of public investment. Unfortunately, advocates of both public and private development sometimes adopt ideological positions and use this technique of comparing an idealised vision of their preferred form of development to a more realistic practical model of the alternatives which indicates the unmanageable problems which may occur. Technical experts often adopt similar thought processes which bias their judgement. Technological optimism in the groundwater field has tended to result in modern solutions with assumed rates of development, levels of cost and operating efficiency. A vision of the best has all too often proved the enemy of the good.

5.7 High Rates of Use

Private farmers do obtain high operating efficiency. By adopting measures to avoid breakdowns and by obtaining prompt repairs, private operators can obtain high rates of use, reduce the capital cost per unit delivered and avoid what can be the extremely high cost to agriculture of unscheduled breakdown. State tubewell users in many countries complain, as in India, 'of too little water, especially reductions without warning, poor servicing of machinery and, most frequently, failure of the electricity supply' (Pearse 1980). Research into the social costs of unreliable electricity supplies, on the line of the industrial model proposed by Munasinghe and Gellerson (1979), are urgently required for India.

Private farmers of course, cannot be isolated from the effects of electricity failure. Indeed, it is arguable that the vast expansion in the last decade of private wells in the Indian sub-continent has contributed to power demand exceeding generating capacity. Unfortunately, peak pumping demand coincides with peak industrial and domestic demand. Water pumped by diesel units costs in the order of 1.5 to 2.0 times the cost per cubic metre of water pumped by electricity and diesel powered wells are far more troublesome. They generally require continuous supervision (see the next paragraph) during operation. However, diesel fuel can be purchased in advance and the energy supply is thus slightly more secure.

There is some variation and some confused commentary of rates of well use in the public and private sectors. Pearse reports that State tubewells 'have a much higher capital cost than private ones and, to recuperate this, are operated much more intensively. This makes them deteriorate faster and break more often, so that they then tend to become unrealistic, unprofitable, and more expensive to the farmer'. This implies that the public wells break down because of intensive use whereas other observers report much less satisfactory explanations for low utilisation rates in the public sector. Similarly, private tubewells do not always achieve high utilisation rates. In circumstances such as exist in Bangladesh, where spares and fuel supplies are unreliable, low utilisation rates of private wells arise because some farmers reserve their facilities for their own high priority use over many years, and refuse to operate wells for marginal crops or to supply neighbours.

The following problems were reported to be commonplace with public wells in Thakurgaon project area in Bangladesh (MacDonald & Partners 1980): unreliable electricity supply; pump or motor unit breakdowns; inadequate farmer interest, incentive and involvement; poor channel distribution facilities; poor irrigation practice and water management; high infiltration rates; lack of extension advice; virtually free water and consequent sloppy water use. It is considered that the first two problems were the prime cause of the third, fourth and fifth problems. This is not an atypical list of public groundwater project problems in Asia.

Private wells which are generally cheaper and simpler, if technically inferior in engineering terms, have performed much better than was expected in the early 1970s. However, there are, to our knowledge, no reliable ex-post evaluations which record the reliability of engines, pumps and, most importantly, the well screen and pipes. Budgets comparing high-cost, 'modern' and low-cost 'local' technology still have a weak empirical content, particularly so for the low-cost options. If technology assessment is to be generally adopted to help selection of an appropriate set of engineering components, the analysis must ensure that they are judging all options by similar standards and criteria.

Public projects usually involve high technology and thus high reliability but if reliable field studies were carried out, they may confirm what is already suspected - namely that cheap local low-cost wells are more cost-effective, despite a very much higher failure rate. Engineers would not then have the usual task of designing with modern, first class technology for high reliability and minimum failure rate. Seeing merit in second best is a mental attitude more often found in the economics profession than in engineering.

The main technical trouble with groundwater schemes concerns the maintenance of pumps and motors. Mechanics with sufficient skill are not easy to find, nor is it easy to train an adequate number and to make sure that, when trained, they will remain in the village to carry out the required work. The urban private sector always has a demand for trained mechanics and a large purse to pay them. Increasingly the demands of Saudi Arabia and the Gulf States and other oil-rich developing countries have drained mechanics, and indeed many and various skilled workers, from the Indian sub-continent especially. This problem rather militates against sophisticated modern and efficient machinery except perhaps for a few large public projects. Recently there has been a marked tendency to go back to the heavy single cylinder diesel engine and to use centrifugal pumps wherever possible. These can be maintained locally, whereas the high speed diesel and deep well turbine pump is a much more difficult proposition.

Private well owners have every incentive to run their wells strictly in line with agricultural needs and, in consequence, there is the minimum wasted water production. Furthermore, although their discharge will be perhaps only 15 to 30% of public wells, and therefore seepage losses in distribution are a much higher proportion of the pumped water, the fields are generally close to the well. In addition, the application efficiency of the small well is enhanced by the field manageability of discharges of the order of 15 to 30 l/s. In such circumstances the overall system water-use efficiency of private wells is likely to be much higher.

5.8 Low-cost Innovations

Private initiatives in the last decade have produced a remarkable range of ingenious inventions and use of cheaper local materials. The bamboo tubewell (Clay 1981), the use and various adaptations of the hand pump for irrigation in Bangladesh are examples. Technical solutions to institutional problems are sometimes found. For example, Clay reports that cheap locally sunk shallow bamboo tubewells enable farmers to insert a well in each of several fragments of land. With the engine and pump made mobile by mounting on a bullock cart all the farm can then be irrigated economically. Pump contractors have also emerged who will provide this service. Inevitably any benefit that appears also creates new offsetting problems and so it is with the mobile engines. For they can also be used to power threshing machines after the irrigation season and this development threatens an important income and food source of landless labourers, poor women and other low-income groups who traditionally earn a major part of their livelihood from threshing.

In poorer areas or where holdings are traditionally small, the individual farmer can afford neither to construct a well nor to operate and maintain it. In these circumstances some form of co-operative or joint ownership may arise. It is normal for the initiative to stem from, and have the direct or indirect financial support of, the Government. Generally a small group is a better proposition than a large one, particularly if it is based upon a family link, although it is an economic fact that a large well is potentially cheaper than a small one in terms of cost of water delivered. Government support often takes the form of a loan to the farmers' group to construct a well, and this is repayable on very favourable terms. Thereafter the operation and maintenance is a matter for the group. This is the principle of a number of the World Bank IDA-funded agricultural credit projects in Indonesia.

In Bangladesh thousands of wells are being sunk under the auspices of the parastatal body Agricultural Development Corporation (ADC). The authority is funding the capital development and handing over wells to farmer groups for operation while ADC will carry out the maintenance. Charges, yet to be decided, will be made by ADC against the operating group.

In Bangladesh in 1979 the estimated cost (Stutley 1980) for an efficiently used low lift pump and a deep tubewell was Taka 410 to 545 and Taka 1 630 per hectare of boro paddy, respectively. However, the cost to the farmer of hiring from ADC was only Taka 85 and Taka 185, respectively. On a similar basis it is estimated that the cost for manual pumping with a hand pump, with 20% hired labour, was Taka 1 740 per ha.

As with all co-operative enterprises, there is a great difference in the success level achieved between co-operatives imposed from above by the Government and those spontaneously arising from the farmers' own initiative. Northwest Bangladesh is an example of the former type and has resulted in a number of problems. Spontaneous farmer co-operatives invariably perform better than super-imposed groups. The Kediri-Ngandjuk Project in Indonesia is one example where this approach is developing really successfully - admittedly after a slow start.

In most economic appraisals, the secondary effects of linkages (so called multiplier effect) are assumed to be equal for all development options and are thus ignored in assessment of costs and benefits. In the case of public and private tubewell development this may lead to serious error because of the different technology each development generally assumes. In Table 2 the main alternatives are presented in a somewhat polarised fashion. Numerous mixes of design components are possible but the alternatives, set out in Table 2, are the main 'packages' selected. The smaller, locally constructed, often locally manufactured, more easily repaired engine and pump, and locally constructed screen and pipe undoubtedly induce more local employment.

The relative economic efficiency of the two options depends upon numerous other factors such as rate of installation, rate of failure but, as experience has evolved in the 1970s, the simpler technology has become more favoured for private and public schemes. Criteria relating to cost-effectiveness, technical performance and others discussed in this section may not be the only or even the most important considerations. Thomas (1975), in an extremely well documented and well argued study, concludes his analysis of a groundwater technology choice : 'Ultimately, it was the organisational requirement of the implementing agencies, including the aid donors, that determined the choice of tubewell technology for East Pakistan. The actual decision-making, such factors as risk avoidance, appearance of modernity, established procedures, familiar techniques and, by no means least, control, outweighed the development policy objectives. It is in these factors that an understanding of decisions as to choice of technology must be sought' (p 57).

TABLE 2

Technology Options for Public and Private Wells

		Public projects	Private wells
1.	Drilling technique	Power (Contractor) >25 cm diameter >40 m depth Imported rigs	Manual percussion or jet <25 cm diameter <40 m depth Local rigs
2.	Employment in construction	Relatively low skilled	High, largely unskilled
3.	Power source	Normally electricity	Diesel, increasingly electricity
4.	Type of engine	Electric or high speed diesel	Slow speed diesel
5.	Type of pump	Shaft pump or submersible	Centrifugal/shaft pump
6.	Screen material used	Stainless steel PVC, fibreglass	PVC, brass, coir, bamboo
7.	Local industry linkages	Low	High

Much of the argument on appropriate technology abstracts from a careful specification of the problems. In particular, argument is often confused when potential and actual results are not clearly defined. Table 3 compares the main issues in the public versus private debate and shows why clear specification of assumptions or empirical results is necessary.

We conclude with a paradox. Farmers operate wells efficiently but cannot even conceive the problem of managing an aquifer. Public authorities can manage an aquifer but cannot operate wells efficiently for their best agricultural use. Striking the right balance is not easy and certainly varies from project to project. Clearly in the future, all wells will have to be licensed and the number and discharge restricted to avoid over-exploiting the resource. If this can be enforced, then there are clear advantages in allowing the farmer or farmer group to operate and integrate groundwater into the existing surface water system. This will always be easier where groundwater quality is good but will require a considerable extension effort when it is not. There is no doubt that Government agencies have been successful in stimulating such developments and that lending agencies have made a contribution by their support and encouragement. However, with or without public sector intervention, it seems likely that small farmers may get a less than proportionate share of groundwater in the next decade.

TABLE 3

Summary of Potential and Actual Achievement

		Mobilising Resources	Speed	Water Use Efficiency on Farm	Integration with Surface	Integration with Drainage	O & M Reliability
Public	Potential result	Poor	Rapid	High	High	High	Good
	Actual result	OK through aid	Slow	Low	Very poor	Poor	Poor
Private	Potential result	Good except for very small farmers	Initially slow then rapid	High	Poor or moderate	Poor	Good
	Actual result	Often subsidised credit	Fairly slow	High	Often quite good	Poor	Good

6. MANAGEMENT AND DEVELOPMENT CHOICES

6.1 Conjunctive Use

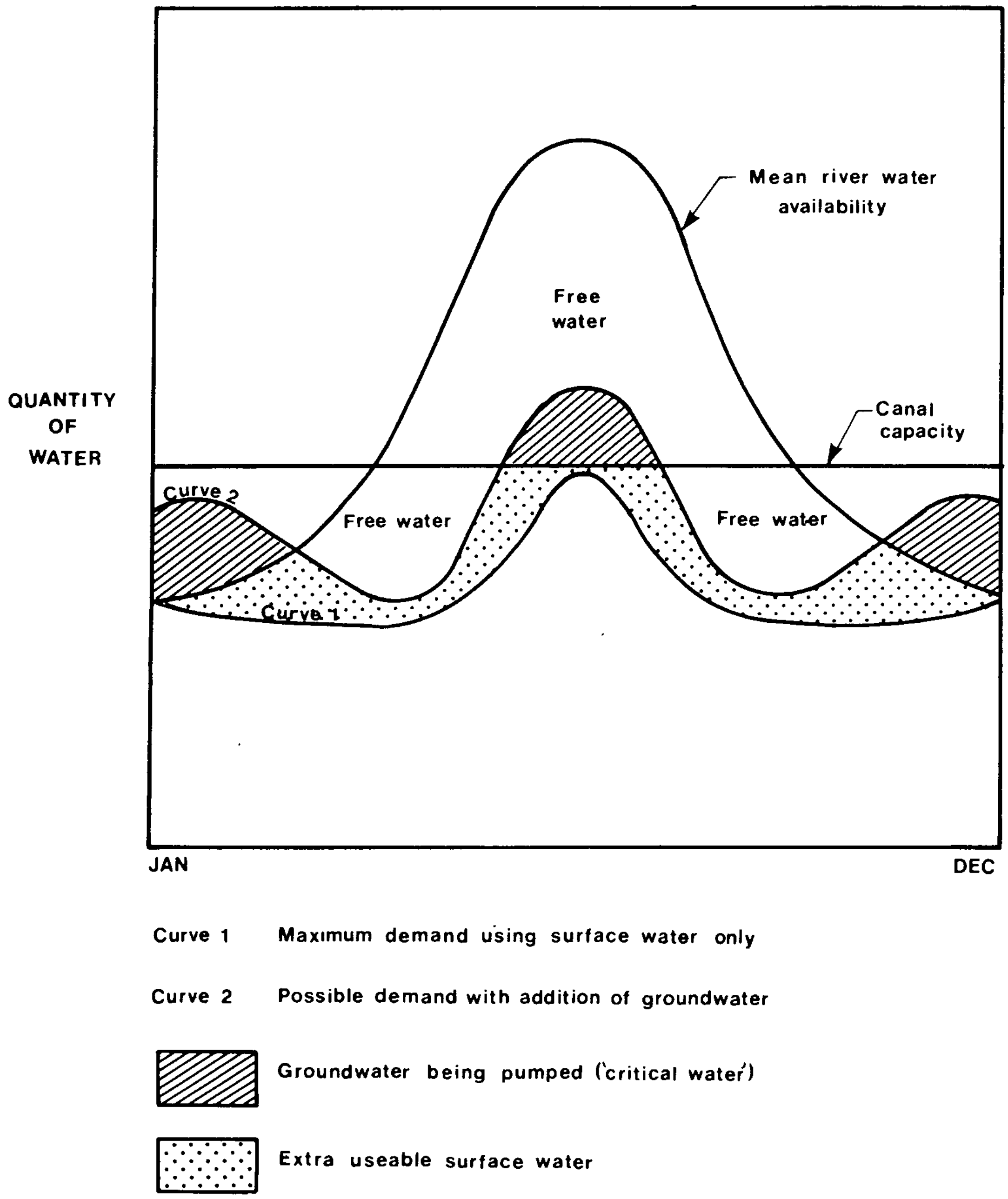
Returning to the question of conjunctive use of water resources, there is no doubt that for some countries this must be the way to make the optimum use of water resources. Equally, it is fair to say that at all levels the possibilities are widely ignored. There is even considerable rivalry between departments operating surface water and those involved in groundwater. In at least one case (Bolivia) two different authorities have put up schemes - one using groundwater and the other surface water - to irrigate the same area of land. Among planning engineers, who should know better, there often appears to be a preference for the water which can be seen, that is, water stored in a surface reservoir behind a dam rather than a consideration of the possibility of developing groundwater or of conjunctive use.

To some extent, conjunctive use has been forced upon countries where surface irrigation sources have been fully utilised and the way forward must involve supplementing surface sources by groundwater, especially in those cases where there is a drainage benefit from groundwater pumping. This is the common feature of many projects of the Indo-Gangetic Plain.

For irrigation projects the manner in which groundwater may be used varies from project to project. In some cases, it may be used to bolster an erratic rainfall in order to ensure adequate yields; in others, it has been used to extend the cropping season or even to grow an additional crop during the dry season (Indonesia and Bangladesh). Integration with existing surface water irrigation systems immediately suggests a further range of possibilities, such as the use of additional surface water that, on its own, would be insufficient for a crop but would be adequate if supplemented by groundwater, at either end of the season or at the peak. In these circumstances it may also be used to start irrigation earlier in a season before surface water and/or rainfall become available and thus grow a higher value crop or provide better land preparation than would otherwise be possible.

Crop diversification and increased intensity give the farmer additional insurance against the risk of failure of a particular crop. Increased cropping intensity brings its own technical problems and inevitably new risks. However, in the case of more water they must be considered justified judging by the rapidity with which opportunities, once known, are seized by farmers. Figure 14 illustrates how the judicious use of groundwater can make better use of surface supplies in a situation like that obtaining in the Indus system of Pakistan. The river has a high summer peak and a low winter flow. The general shape of the cropping pattern demand curve is shown in Curve 1 and it can be seen immediately that, by using groundwater in the winter, the total water available can be raised to the level of Curve 2. This requires the use of a substantial quantity of river water that would otherwise be wasted to the sea. In the real case the matter is much more complicated than this and involves optimising between river flow, rainfall, surface storages and groundwater.

FIGURE 14



Mean river water availability
Free water
QUANTITY OF WATER
Canal capacity
Curve 2
Free water
Free water
Curve 1
JAN
DEC
Curve 1 Maximum demand using surface water only
Curve 2 Possible demand with addition of groundwater
Groundwater being pumped ('critical water')
Extra useable surface water

6.2 Critical Water

At crop levels the concept of 'critical' water can be of value in considering the enormous contribution that groundwater can make. Figure 15 illustrates the principle in schematic form and is based on the fact that water is more valuable for a particular crop at one time than it is at another. In the extreme case, with a single crop, it may be that, if water is not available by a certain date, the crop cannot be planted at all - in which case, provided that there is no alternative use for the latter water, the value of the increment of water necessary for planting takes on the net value of the whole crop. Once it has been planted, then perhaps the next increment has the most value until, at the point of harvest, the marginal value of water is zero.

The 'critical' water concept is valid even if the extreme case is severe. Generally it is possible to plant another crop if there is no water to plant the most profitable first choice. However, there is obvious merit in using groundwater to plant the first choice crop, if the river rises too late or rainfall fails to arrive to allow this to be done. If the argument is applied to a diversified cropping system, then options grow and other resources may become a constraint. Planting dates are staggered and the total water demand pattern becomes smoother. It should therefore be possible to optimise the cropping pattern to fit in with some programme of planned water availability (perhaps allowing for some deficiency on a probabilistic basis). The principle envisaged here is that there may be better overall returns to a system that is deficient - say, for a month, one year in five - rather than adopting the conservative assumption restricting the area cropped so that there is no water deficiency in any year.

6.3 Joint Operation of Electricity and Groundwater Projects

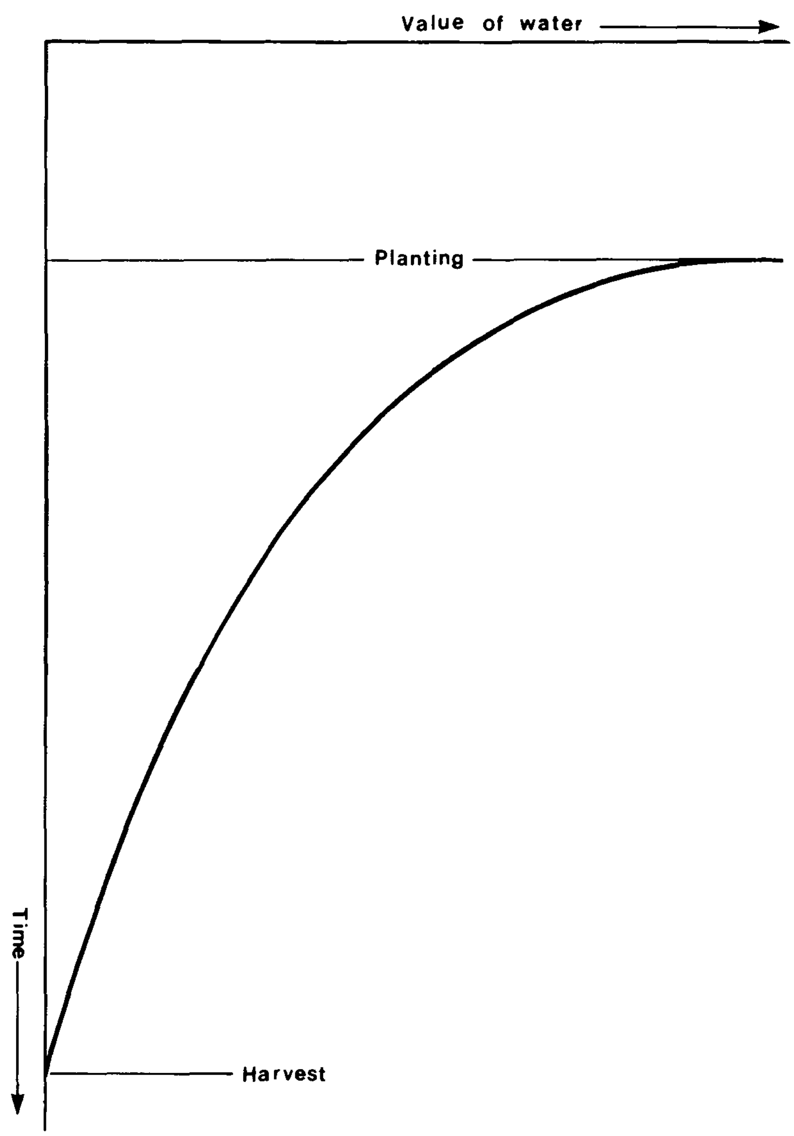
The management of large aquifer systems can sometimes involve other aspects of national development, if the overall economic possibilities are to be considered. Many public projects, involving a large number of wells, opt for electrically driven pumps together with the necessary power generation and transmission system. In developing countries the power needed for such a project can be a major part of the total power requirement. It can then become a very important element in optimising power operation in that it is ideal for peak load shedding. Unfortunately, this thought often occurs after the event rather than during the planning stage. Thus in irrigation projects the farmer may lose his water supply for a vital two or three hours a day. Attention to this matter during the planning process might involve the installation of larger wells or a greater number so that the required quantity of water is delivered and a planned load shedding schedule established. This kind of planning requires a degree of co-operation among the various government departments - which is usually noticeably absent.

The potential for large gains within the electricity sector from public operation is illustrated in another way by the following example where public tubewell installation enhances the operation of a storage dam.

In hydro/irrigation storage schemes there are generally complementarities between demand for power and demand for irrigation water. When it is warm the crops transpire and people switch on fans and air conditioners, water is then

FIGURE 15

Groundwater Pumped ('Critical Water')



released through turbines to produce power and the diverted water into irrigation canals. Unfortunately, demand patterns do not always match and when, say, agricultural demand is greater than electricity, power is wasted by the discharge bypassing turbines. Such a situation exists in northern India during the winter rabi sowing season (October to early December). The reservoirs are full following the monsoon but power engineers wish to hold the water until power is required and, thereby, to retain the maximum head which means maximum power per unit of water. On the Bhakra system an ingenious solution was proposed by Harbans Singh (1964), whereby part of the releases for agriculture were used to generate power for banks of tubewells sunk alongside canals of the Bhakra system. This tubewell water was used by agriculturalists and it enabled engineers to retain dam storage until electricity demand matched irrigation needs. It was a neat proposal that simultaneously enabled both irrigation and firm power levels to be increased. Such a scheme will pass the first of two economic tests, if the present value of extra power produced from discharging, according to demand from a higher head plus the net present value of the additional irrigated area, exceeds the present value of the wells and pumping costs. Second, this investment should give a higher return than alternative schemes such as increased thermal power station capacity. Minhas et al. (1972) evaluated the Bhakra proposal and showed savings could be substantial. Installation of 28 m^3/s (1 000 cusec) tubewell capacity increased firm power by 99 MW (assuming 90% confidence level) at 30% of the cost of thermal power, without considering the net value of additional irrigation.

Such a development shows the potential savings of a public scheme. It is conceivable that similar gains could be obtained from private wells particularly if subsidies were given for installation and/or operating wells in crucial periods. However, it is very unlikely that the intensive level of use for short periods could be obtained without a very high level of installed capacity.

6.4 Integrating Surface and Groundwater

A further management problem arises from integration of groundwater with an existing surface water system. In irrigation projects management problems can start with the farmer who is often traditionally suspicious of new developments (often with some justification!). For example, both in Egypt and the Indian subcontinent the river waters are silty whereas well water is clear. The silt is thought by farmers to have both tangible and mystical properties and thus river water must be superior to groundwater. Undoubtedly the notion that well water should be paid for by the farmers gives a certain vehemence to such arguments. Where salinity is present in well water, the resistance of farmers to its use is clearly valid.

Another problem arises in constructing the new watercourses which are needed to take care of the extra water supplied. Normally this is a matter for the farmers themselves but, because of their initial resistance and the difficulty of designing adequate mixing facilities where the two sources are to be used together, the task often falls on the Government. This is made doubly difficult when the groundwater is being developed by a different department from that operating and maintaining the irrigation system. There are glaring examples of these crises of co-operation in a number of recent projects. The farmer problem can be overcome by patient demonstration and encouragement. This can take several years but projects like Kediri-Nganjuk in East Java have now become an outstanding success after a somewhat chequered early history. Farmers there are now demanding new wells and are actually growing up to three crops a year on land where it was only possible to be sure of one crop before. The recent loud complaints of landowners about rises in wage rates in this area are the best (albeit anecdotal) evidence of employment creation (R. Ryman, field investigator, private communication).

Much more interest needs to be taken with design and operational performance of novel distribution facilities. Low pressure pipe systems (Gisselquist 1979) and low-cost channel linings (Khair et al. 1980) need field assessment. Pumped water is costly and every effort should be made to obtain the maximum economic efficiency in field distribution. There is much evidence that this aspect of irrigation development - called the 'distribution non-system' by Gisselquist, continues to be neglected despite the economic potential.

In north Bangladesh four public agencies as well as private farmers are responsible for groundwater development with no overall authority (MacDonald & Partners, 1980). Clearly the management of aquifers and, even more so, of integrated consumptive use systems is a complicated and sophisticated matter. It is beyond even the conception of the farmer or private well owner and, while

Government may understand the concept, the degree of departmental co-operation required may defeat the best intentions. Consequently, most groundwater developments are on a somewhat ad hoc basis tied together with the vague notion that something better ought to be possible. Mercifully, it is difficult to do any permanent damage in most cases and the worst that happens is usually an inefficient use of resources and considerable inconvenience to some users.

Groundwater projects sometimes need to be carefully integrated with each other. In a country such as Bangladesh, with a large private investment in shallow open wells and hand pumps operating from shallow aquifers, public projects using big wells could produce long term, or even seasonal, local or regional falls in the watertable. This would create considerable hardship, as the bulk of the drinking water and some irrigation water could be drawn from the shallow sources. In north Bangladesh where it is proposed to sink 2 700 deep tubewells (60 l/s) and 3 600 shallow tubewells (15 l/s),there are more than 8 000 handpump wells. In the project design allowance has been made to compensate owners of 4 100 wells which will be affected part of the year, and 2 200 hand dug wells affected but not substituted for by the new project wells. Compensation costs are less than 1% of capital costs. Although there are grounds for concern regarding the practicalities of fairly compensating those affected but not benefitting from the project, the potential benefits from expanded and more reliable irrigation in the region are expected to yield an internal rate of return between 32 and 55% (MacDonald & Partners, 1980). This example shows the importance and potential gains from an effective overall public authority.

It also highlights the need for continual, or at least sporadic, independent audit of public authority performances. The projected rates of return will be valid only if those that suffer are compensated, if the modern tubewells perform as the designers anticipated and if operation, maintenance and management reach projected standards.

6.5 Rehabilitation versus New Projects

There can be no doubt that in the groundwater sector the most economic use of public investment resources is to maintain and, failing this, to rehabilitate ailing projects. The original investment is a bygone or sunk cost and therefore all incremental returns, in principle, can be attributed to the maintenance of rehabilitation expenditure. The poor standard of operation and maintenance over long periods on many projects is well known from field reports and is given tangible form in surface irrigation by recent rehabilitation projects in several countries. Some of the naturally most favoured regions were the first to be developed and will reach the highest level of production after rehabilitation.

Operation and maintenance is neglected for several inter-related reasons including:-

(i) recurrent budget shortfalls (declining economic activity in recession, inflation fought by holding public sector prices, political reluctance to charge economic rates, etcetera.);

(ii) increased recurrent budget obligations (many low or non-revenue raising projects and policies, shift to poverty oriented projects, etcetera.);

(iii) lack of political, administrative and technical support for unglamorous, routine maintenance activity;

(iv) diversion of finance, personnel and other resources to provide local support for new (aid) projects; for a more complete account see Carruthers 1981.

Without adequate maintenance then either rehabilitation or dereliction becomes inevitable. Despite high returns, rehabilitation of groundwater projects is grossly neglected because :-

(i) there is a general reluctance to admit project failure;

(ii) general ignorance of performance (poor monitoring and evaluation among Government, consultant, operating agency);

(iii) local cost higher proportion than new project;

(iv) project area had 'had its share' and other areas need investment;

(v) rehabilitation lacks the challenge, excitement and status of new projects.

Some of the measures required which could improve project operation include programme lending with agreed components for O & M, easing budget pressures by rescheduling debts, a more liberal interpretation of aid terms to include recurrent budget support, more rehabilitation or even O & M projects, an extended commissioning phase for projects, more political protection of the recurrent budget and professional training and rewards for staff, more tough measures on pricing especially in inflationary periods (Carruthers 1981).

The external and internal pressures creating shortages of recurrent finance seem unlikely to be relaxed in the short-term. Indeed, it is conceivable that resources could become more not less scarce with obvious detrimental effects upon operating standards. Paradoxically this deterioration might assist rehabilitation because such investments satisfy aid donor 'capital' aid criteria.

7. AQUIFER MANAGEMENT

An aquifer can be looked upon as a repository for water. If there is the opportunity for public sector control, it can be operated as a reservoir or a mine and this depends largely on the degree to which exploitation is balanced by replenishment.

In many large aquifer systems the concept of balanced recharge is a dynamic one. The massive aquifer system of the Indo-Gangetic Plain is an example of such a condition, in that the more that is pumped from the aquifer the higher the recharge from the river and canal system becomes. However, there is no doubt that inducing recharge from the river system by pumping, and lowering the groundwater level does reduce the amount of surface water available in the canals and rivers.

For part of the year, when rainfall or surface water is available or when crop demands are low, the induced recharge will have zero farm opportunity cost. Surface irrigation at this time is often wasted by careless irrigation or inadequate canal operating policy, and thereby adds to short term and long term waterlogging and salinity problems. Public authorities would derive benefits if they had the ability to lower the watertable, in advance of these periods, to below root zone and create a 'buffer' soil volume.

In most circumstances induced recharge will have a positive opportunity cost and any decision models for listing operating policies should have this assumption incorporated. There is thus a trade-off between quantity pumped and consequent surface water depletion. This is not merely a spatial concept - there are also temporal aspects. For example, it is possible to pump groundwater in the season of low surface water flow so that there is considerable drawdown, provided that the consequent depletion can be recharged in the subsequent flood season.

The concept may be extended further in that it is not strictly necessary to balance the recharge from season to season. If in the longer term an overall balance is achieved, then we may develop an optimal regime for the operation of the groundwater reservoir which allows a far greater degree of flexibility than can be normally associated with a surface reservoir. Thus, if there is sufficient data on rainfall and river flow and infiltration rates, the groundwater can be operated to achieve a long term balance and hence to allow a greater average volume of total water to be utilised than would otherwise be possible. This involves the concept of optimal conjunctive use of resources which can be applied on a local or regional scale.

A good example of exploiting the spatial and temporal characteristics of a groundwater aquifer, by a management scheme to help cope with severe peak water demands is provided by the River Clwyd Augmentation and Abstraction Scheme in Wales. In this case a very pronounced seasonal peak for urban water is caused by the seaside tourist industry. This peak may coincide with low river flow, inhibiting the use of normal groundwater supply because geological conditions are such that pumping in the dry period immediately has a detrimental effect upon river flows. Investigations showed the extent of the groundwater field and it proved possible to draw augmentation water at peak period from groundwater, put into the river upstream to maintain river flows downstream, thereby allowing continuous pumping of the drinking water wells without risk of deterioration of river or groundwater quality.

7.1 Mining

In the event that there is no replenishment of the aquifer, it is then necessary to consider mining. A similar situation exists when recharge is insufficient to meet any worthwhile demand. Such a process cannot go on indefinitely and it is possible to argue that equilibrium will eventually be established without public interference and that efficient farmers will then pump recharge. Such a conclusion neglects inter alia the additional costs of pumping the recharge, the possible loss of storage capacity and the incidence of benefits.

The whole concept of groundwater mining is an emotive subject. Whereas the mining of mineral resources is fully acceptable and, for oil, the merits of mining are unquestioned, there is a general reluctance throughout the world to regard water as an exploitable resource. Looked at with cold logic, however, there are no differences in principle between oil and water mining. The earth's resources are there to be used intelligently and this must involve consideration and balance between our immediate needs and those of succeeding generations.

The question is often raised whether permanent mining should be allowed, and one finds that the principle of mining is commonly opposed just as strongly in arid areas as in the temperate zone. The leading financing agencies appear unsure of their attitude on the question and unwilling to treat groundwater as an exploitable resource. Yet in many parts of the world there is no viable short term alternative; mining is going on and, without it, no economic activity could be generated. In these situations mining groundwater can be invaluable in buying time while long term resources can be found.

Several examples could be cited to demonstrate such activities. The first is in and around Riyadh (MacDonald & Partners, 1975) in Saudi Arabia. Here the whole of the water supply for domestic purposes, gardens, a little agriculture and industry is mined. The original superficial aquifer has been exhausted and water is now drawn from the Minjur aquifer with wells varying from 1 200 to 1 800 m in depth. The Minjur piezometric level is falling and the next phase of water development will be from another aquifer known as the Wasia. Both aquifers have very limited recharge and are being mined. However, the Wasia resources are expected to last, at the present rate of development, long after the fossil fuel used to power the abstraction pumps has been exhausted. Every aspect of development and all economic activity arising out of what has now become a great city is dependent entirely on this mined water. However, a long term future supply from desalinised Arabian Gulf water is envisaged. An exact parallel to Riyadh is the city of Phoenix in Arizona which relied during its development on mined ground-water to the point of exhaustion and eventually had to pipe water across the desert to meet its needs.

Other examples can be quoted from India. There are areas of over-exploitation of groundwater in the coastal areas of Andhra Pradesh, in the Sharif areas of Bihar, the Anjar-Khedoi and Viri areas of eastern Kutch, the Melisana area of Gujarat, parts of Ludhiana, Jhunjhunn and Kharkar in Rajistan, and in Coimbatore, Salam, Madurai and North Arcot in Tamil Nadu. In some of these areas, such as Gujarat, this activity has raised the standard of some of the farmers' living from subsistence to the point where they can afford modest farm development and allow their children to be educated. Perhaps in the space of a generation it will no longer be economic to carry on mining but meanwhile it would be difficult to deny the benefits to the present generation, even if we cannot put a satisfactory value on them.

A longer period of groundwater development and mining has occurred in Coimbatore District in South India. In 1895 there were 53 500 open wells and, by 1976, 150 000 (Sivanappan and Aiyasamy 1978). The extraction now exceeds recharge with the consequence that water levels in wells are falling, necessitating expensive deepening, sometimes to 50 m or more. Despite this, new wells are being sunk at a rate of more than 2 000 per year. However, it can be no coincidence that, although this district is endowed with scant and unreliable rainfall, poor soils and few mineral resources, it has become a prosperous agricultural and industrial centre. Groundwater irrigation has provided direct benefits to industry, such as food and raw materials, market for pumps and engines, and numerous indirect linkages including a source of capital for industry and enterprising entrepreneurs familiar with operating and maintaining machinery. Although the present rate of groundwater use is not sustainable in the long run, the sound industrial base offers the prospect of alternative paths to development.

Similar situations can be found in Kokkinokhoria in south-east Cyprus (Republic of Cyprus 1980) and in Jordan (Clayton et al. 1974) where groundwater mining has resulted in a temporary, and perhaps fragile, prosperity but one which may create preconditions for new successful forms of development.

It is not simply in low income areas that socially sub-optimal pumping policies take place. Well informed farmers operating high profit systems also fail to recognise their collective interest. Kern County, California, has one of the most productive agriculture systems in the world but by the 1930s serious depletion had occurred. By 1960 the groundwater annual overdraft was estimated to be 900 million m^3 over 400 000 ha of crop per year. Water levels are still falling (1 to 6 m/year between 1955 and 1975) and pumping levels are over 100 m in some areas. In some aquifers this mining has led to land subsidence and therefore some relevelling costs are incurred, but not necessarily by those who benefited from the original mining, and there is permanent loss of aquifer capacity.

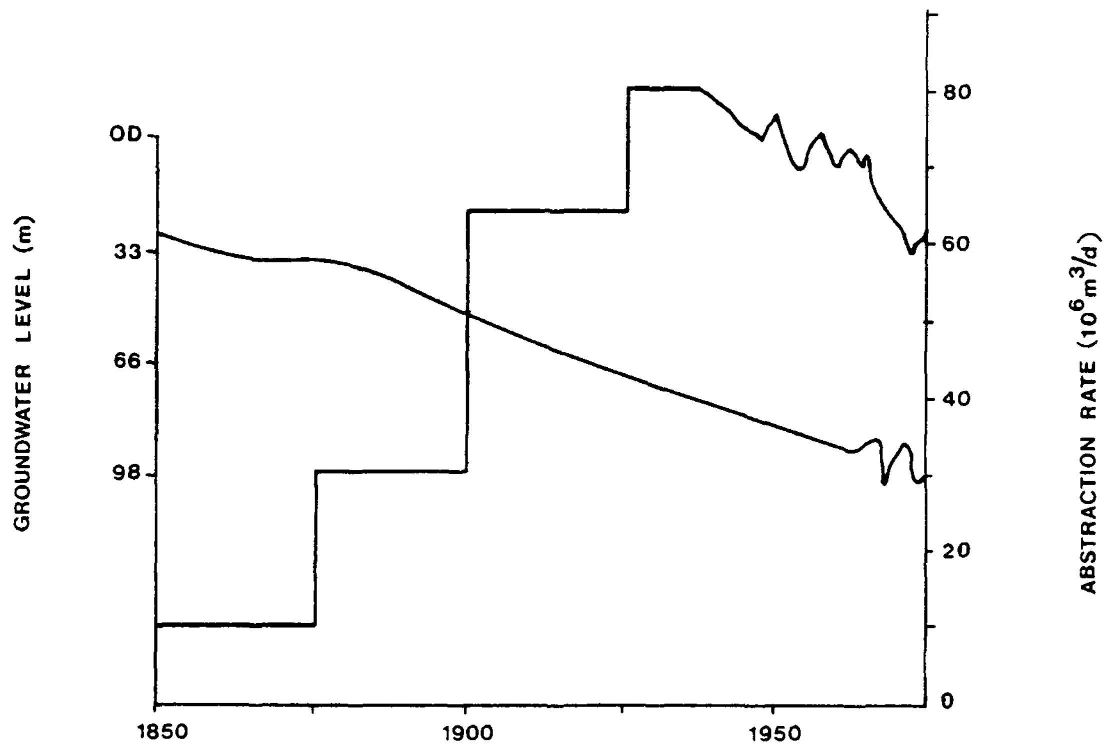
The examples above are from tropical or arid areas where there is little alternative to mining. In temperate countries mining is generally included in planned development only on a temporary basis. Permanent mining is usually the result of intensive but unmanaged groundwater development, as it was in Coimbatore. By virtue of its uncontrolled nature, the effects of such mining cannot be predicted except in general terms; one can forecast, for example, little more than that shallow sources will be dewatered and that surface water supplies will fail because of baseflow depletion.

A good example of such unmanaged mining is the development of the Chalk and Tertiary Basal Sands aquifers of the London Basin (Clark and Stoner 1980).

This aquifer system was exploited through the eighteenth and nineteenth centuries by intensive private development to service the residential, commercial and industrial growth of the city. The increase in groundwater abstraction and the resultant fall in groundwater levels are shown in Figure 16.

The water levels had fallen to such an extent by the middle of this century that the Tertiary Basal Sands were dewatered over some 900 km^2. It was thought that this mining was permanent but at present the problem is being alleviated naturally because of a decrease in demand in Central London.

FIGURE 16



Abstraction Rate from London Basin Chalk and Basal Sands Together with the Decline in Groundwater Levels Under Central London, 1850 to 1965

The problem of mining groundwater can be treated economically in the same way as any other exploitable resource. In the general case when there is some element of recharge, the cost of mining will include two components. The first is the cost of pumping the quantity of water mined; the second is the extra cost of pumping any annual recharge through the extra head which results from the mining.

When q cubic metres of water are mined per unit area from a watertable aquifer with a specific yield of S, the watertable will drop q/S metres. Assuming 65% overall efficiency the extra power needed to pump the existing recharge Q (m^3/m^2/annum) is :-

$$\frac{0.0042\ Qq}{S} \quad \text{kWh/annum}$$

In permanent mining the cost of this power is incurred in perpetuity and, discounting the cost to present value :-

$$\text{Extra cost per square metre of aquifer of pumping existing recharge} = \frac{0.0042\ QqC}{Sr} \quad \ldots (1)$$

where	Q	=	volume of recharge in m^3/m^2/annum
	q	=	volume of water mined in m^3/m^2
	S	=	specific yield of aquifer
	C	=	cost of electricity per kWh
	r	=	discount rate.

The cost of pumping the mined water q per square metre of aquifer is :-

$$0.0042\ qC\ \left(d + \frac{q}{2S}\right) \quad \ldots (2)$$

Where d = original depth to watertable

The total cost of mining the quantity q is therefore :-

$$(1) + (2) = 0.0042\ qC \left(\frac{Q}{Sr} + d + \frac{q}{2S}\right) \quad \ldots (3)$$

If the total cost of mining is less than the net present value of the water derived, then mining is economically justified. In assessing the benefits it should be noted that it is the marginal, not the average, return to the mined water used on farms that is relevant.

When data allow, the above relationship can include a value for the opportunity cost of induced recharge from canals, rivers and lakes. Where mining leads to subsidence and permanent loss of aquifer storage capacity or to direct damage to structures or buildings, provision for these social costs must be made.

The choice of discount rate in economic analysis is often critical. For example, in comparing groundwater development options with surface water, a higher discount rate will favour groundwater because in the latter case a larger proportion of total costs (pumping costs) are deferred, and investment can be phased in line with increasing demand. In the present mining example, a high rate will favour increased and early mining because the level of costs, from the higher subsequent pumping costs, are diminished by high rates of discount.

There is commonly argument as to what is the appropriate rate - the social rate of discount. Several alternative views are possible : should it be identified with the rates of interest paid in the economy by borrowers or those to lenders; with the marginal rate of productivity of capital in the public or the private sector; with the value judgements of decision makers on the weight between present and future consumption; or should it be left unresolved with sensitivity analysis indicating at what level the rate changes the design in a significant way and the problem of choice being faced by other criteria.

The empirical determination of a rate is problematical whatever approach is selected. Rates of interest vary widely, the marginal productivity of capital is difficult to estimate and varies extensively from project to project. Historical choices of rates may or may not be appropriate to guide future choice, and multiple objectives of policy further complicate the issue. It is sometimes argued that investments which imply irreversible changes or those which have very long term implications should have a different (lower) discount rate to give greater weight to the future than a normal social rate of discount. Groundwater mining, in practice, is often irreversible and, if there is significant recharge, the implications of increased annual pumping costs are clearly long term.

In practice, whatever the rationale to explain its choice, the social rate of discount is normally assumed to lie in the range 10 to 15%, although ex-post evaluations show that within any economy there are in practice a wide range of returns from project to project. Typically actual returns to agricultural investment are less than two-thirds of levels predicted at the pre-investment stage with so wide a range as to make the norm of 10 to 15% almost meaningless.

It will be seen from equation 3 above that, in a situation where there is some recharge to the aquifer and Q and q are of similar orders, then the term Q/Sr dominates the cost even if r ranges from 0.05 to 0.2, and the smaller r becomes, the higher is the cost of mining. In these circumstances the discount rate can be used to give an intuitive value of the resource to a succeeding generation. In other words, if we value capital at a lower rate than the assumed current social opportunity cost, then we tend towards preserving the resource and to restricting mining.

A case history of an economic assessment of proposed mining in the Lasithi Valley in Crete is given in Kuiper (1965). That study, following similar principles to those outlined above, concluded that the cost of mining would be \$13 per 1 000 m^3 compared with a return from increased agricultural production of \$8 per 1 000 m^3 of water. The proposed scheme was therefore shown to be economically unjustified.

Howe (1979), reporting work by Cummings, showed a contrary situation in La Costa de Hermosillo, Mexico. By modelling both the aquifer behaviour and, using a linear programming approach, the agriculture production system, he shows that mining is economical for 36 years. At this time the shadow value or opportunity cost of water left in the aquifer is greater than the cost of alternative surface water from distant sources. By year 36 annual pumping has fallen from the original level of 1 200 million m^3/year to only 380 million m^3/year. In his budgets mining for more than 30 years is economical even though the cost of lifting the water when the optimum point is reached is 70% above the costs in Crete. This illustrates the need for economy specific budgeting and occasional reappraisal of decisions in the light of local and changing economic factors.

7.2 Quality Control

Groundwater often presents quality problems which can be interpreted by reference to previously established standards. Use of such an approach of the problems involved in diagnosing and controlling water quality implies that we have confidence in the quality standards which have been set. For drinking water the World Health Organisation (WHO) standards are probably acceptable, although there are many parts of the world where these standards are not met at present, albeit with some effect on public health. Broadly, WHO define waters with total dissolved solids (TDS) of 1 500 ppm as highest permissible and 500 ppm as the highest desirable limits. Limits for individual constituents are also specified.

The main problem with quality lies with irrigation waters for which the standards are laid down in the 1954 Handbook 60 issued by the US Salinity Laboratory and further refined in 1976 in the FAO Irrigation and Drainage Paper Nr 29. The standards recommended are:-

Good	0 - 700	ppm
Marginal	700 - 2 000	ppm
Hazardous	over 2 000	ppm

Standards are also given for alkalinity as measured by the sodium absorption ratio (SAR) and for toxic elements such as boron. In all cases it is known that these standards are unnecessarily conservative. It is now well known that crops can be grown with much worse water qualities in certain circumstances. Further it is established that, on light, freely draining soils, alkalinity is not a serious problem. In fact, it is only a severe problem in soils containing a significant proportion of clays. Even the boron standards were established in pot trials and it is established that in the field rather higher levels can be tolerated.

To illustrate this problem, we have observed excellent vegetables on light soils in Pakistan growing with water of 3 000 ppm and in Bahrain acceptable crops at the 7 000 ppm level. Reports from Israel indicate success at 10 000 ppm. In deciding on minimum acceptable quality standards for irrigation water, not only should quantity be a criterion but soil chemical and physical characteristics also need to be taken into account. For example, on a freely drained sandy soil, deep percolation losses will probably meet all leaching needs, and a limited accumulation of sodium will not prove harmful over the short term. On a heavy clay, however, where percolation will be slow and where an increase in sodium content will result in further dispersion and loss of structure, provision for leaching and quality of water will be much more critical. A good irrigation land suitability classification should take account of all the factors including quality and availability of water.

Milton Fireman, in his excellent 1968 paper, after reviewing world wide experience in the use of saline irrigation water concludes :

> "It is clear from the foregoing that there are no absolute critical limits for salinity, SAR or any other chemical property of water which define the economic utility of an irrigation supply. Within reasonable limits, water of virtually any character can be used for economic development of arid lands".

Although there is a considerable body of literature on the subject, there is a need to produce a set of revised standards and technical recommendations for watering regimes as a matter of some urgency, so that our attempts at groundwater control can proceed on a rational basis. It is recognised that the matter is not simple. The physical characteristics of the soil are involved as is the chemistry of both the soil and water.

There is no doubt that, if poor quality water is used for irrigation, then more of it is required to provide adequate leaching and thus avoid the accumulation of harmful salts in the soil. The important point is, that in discussing the minimum acceptable quality standards, the quantity required is also discussed.

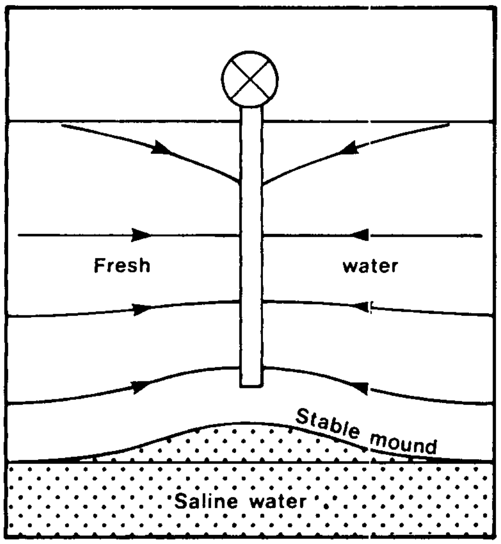
Water quality in an aquifer is seldom uniform. Sometimes the presence of aquitards (impeding but not impermeable layers or zones) define layers of differing quality. In large alluvial river valleys the groundwater is often fresh in the region of the present (and any previous) meander flood plain, but gradually deteriorates with distance from the river. Deterioration often increases with depth. The reverse situation where saline water overlies fresh also occurs, but it is less common. To establish the actual condition, a detailed and carefully conducted investigation is necessary, involving drilling boreholes, logging them geophysically and pump testing at various intervals.

For conditions where there are distinct layers confined between aquitards, it is a relatively simple matter to exclude most of the poor quality water, by placing blank pipe opposite proven poor quality and doubtful sections, rather than well screen.

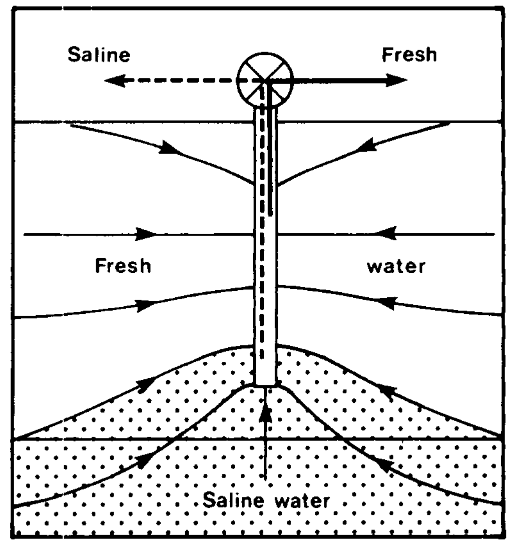
In the common condition where fresh water overlies saline and where there is no aquitard between them (that is, the aquifer is uniform), then various skimming techniques can be used. For example, it is possible to design a well to terminate within the fresh zone with the bottom at some distance above the saline interface. Under these conditions there is a possible rate of pumping where the denser saline water is drawn up into a mound under the well, which becomes stable and does not actually enter the well. The pumped water under this condition will then always be fresh. However, for nearly all cases encountered the pumping rate for such a system is small and the water is thus costly. Another possibility is to pump at a higher rate and accept that the saline water will enter the well at some future time. Provided that time is sufficiently long, the resulting cost of water can then be economic. This is known as a 'limited life-time well'. Where for institutional reasons it is not possible to obtain public control over well withdrawal, all wells are potentially, and in all likelihood, in actuality, limited life-time wells.

Yet a third possibility is a scavenging well which relies on the fact that the streamline geometry of a well is fixed once it is established and hence it is possible to define the point in the well below which the incoming water will be saline. If two pumps are then used, the fresh water can be pumped quite separately from the saline and the latter discharged to waste. Figure 17 shows the principles involved in the methods described above. For all three cases the system geometry can be varied and different pumping rates can be used. Optimisation procedures are available to determine the most economic configuration.

FIGURE 17



SKIMMING WELL



SCAVENGING WELL

Saline water intrusion can be a problem in some coastal regions when sea water has access to an aquifer. Excessive pumping of fresh water causes a wedge of sea water to further invade the aquifer and eventually causes wells to become saline. Figure 18 shows the condition. In many cases the fear of this intrusion occurring is more common than the actual occurrence of the phenomenon but nevertheless it has been observed in some instances. In ideal circumstances the shape of the intrusion is known as the Ghyben-Herzberg wedge and and the extent of the wedge can be defined mathematically. For more complex cases a mathematical model is essential. Recently an advanced model for this purpose has been used in Bahrain where sea water intrusion from the Arabian Gulf has become a critical problem (MacDonald & Partners 1980).

Two solutions have been tried to combat saline intrusion. One involves the use of injection wells in a line along the coast to create a hydraulic potential to hold the wedge back, and the other involves pumping the wedge itself with sufficient installed capacity to balance the inflow. A third possibility to reduce the rate of intrusion is to reduce pumping in the aquifer itself. With the aid of a model a combination of these possibilities may prove to be the economic option. Certainly, such a system is susceptible to the optimisation process.

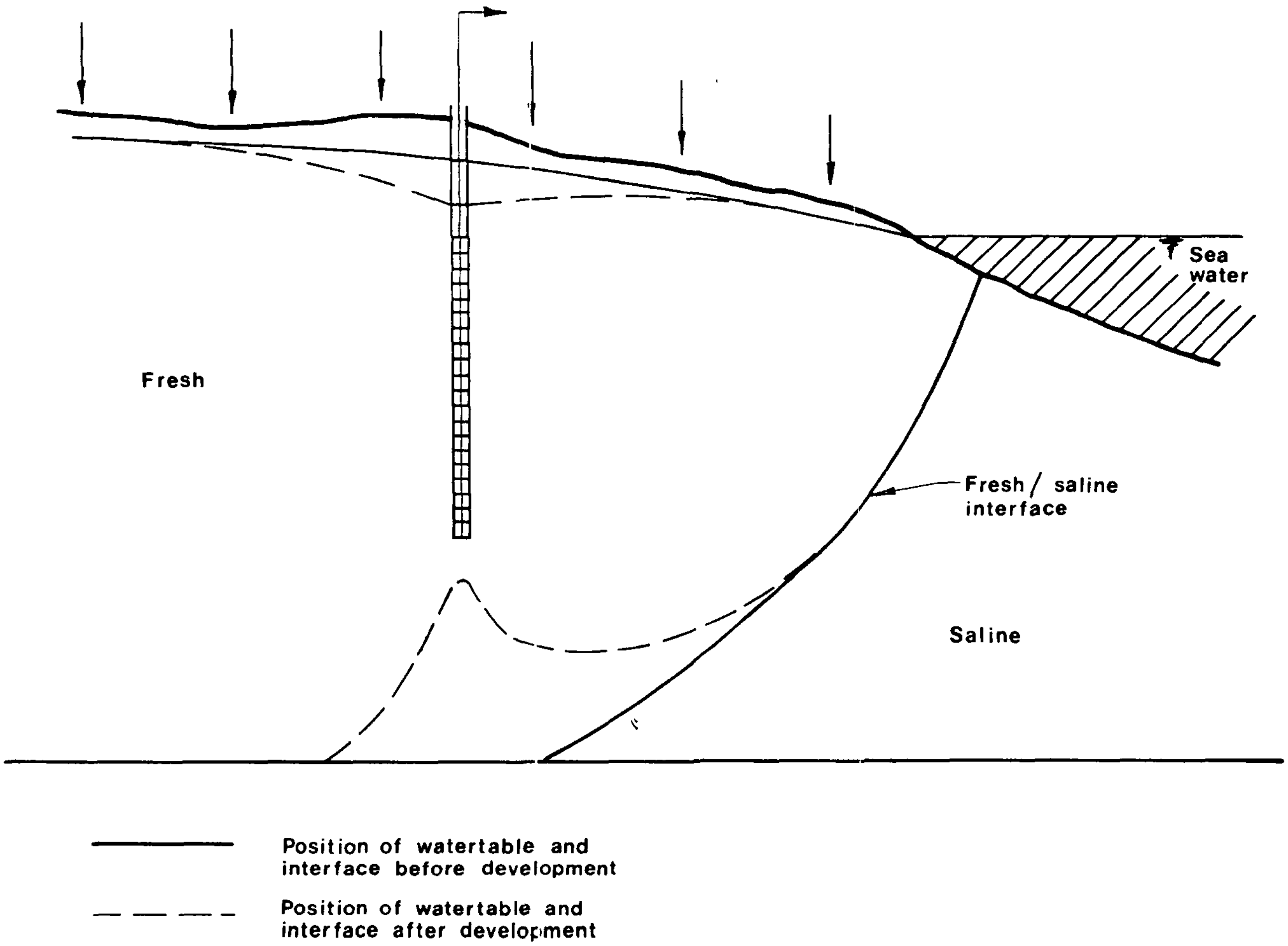
With the full development of surface irrigation in many river basins, there has been a decline in river flows, an increase in sea water intrusion and subsequent groundwater pollution. This is a growing problem but special measures to prevent damage such as barrages or embankments are costly to erect and maintain and cannot generally be economically justified.

Another form of intrusion is the invasion of one aquifer by water of inferior quality from another. This can happen when an aquifer is overpumped and the piezometric pressure is seriously reduced, causing the water to move from an adjacent aquifer which was previously in equilibrium before pumping started. Such a case is occurring at the present time in Bahrain where water from a lower saline aquifer is upwelling into the overpumped upper aquifers. Again, the use of a model is almost essential to define the condition and to test possible solutions.

The problem with saline intrusion from whatever cause is that by the time the condition is recognised the damage has been done. In principle it is possible to exercise some control to prevent the conditions spreading. However, often the optimum pumping regime of private individual well owners will result in a wellfield pumping pattern which is far removed from a socially optimum pattern. Indeed it can lead to rapid deterioration as has occurred in Mehsana in Gujarat State, India.

Groundwater contamination has always been with us - the discovery that typhoid was waterborne arose from the observation that a group of people who died from the disease all drew water from a particular well in London. It is only in recent years, however, that the widespread contamination arising from industrial waste, the use of fertilisers and insecticides have begun to cause general concern. Essentially the problem at the moment is with watertable aquifers because these are the most easily affected - the most intensively exploited and also the most regularly monitored. Deeper aquifers are not normally affected by active pathogens from sewage contamination because they cannot survive in such conditions, but it is sometimes possible to detect excessive nitrite which

FIGURE 18


Sea water
Fresh
Fresh / saline interface
Saline
Position of watertable and interface before development
Position of watertable and interface after development

indicates previous contact with sewage effluent. Deep wells, which are contaminated with active pathogens, usually are damaged in such a way that sewage gains access to the well from the surface. Contamination from agricultural chemicals is increasing but, again, this is largely a surface phenomenon affecting only the upper groundwater so far. This is a position which must be monitored, especially in the case of the more noxious constituents of some insecticides and herbicides whose use is increasing and which are known to remain active almost indefinitely.

Perhaps the most dangerous potential contamination, and certainly the most emotive, arises from the dumping of industrial waste - particularly if it is radio-active - down boreholes. Any such proposals should be carefully reviewed to ensure that usable groundwater is not contaminated by such industrial waste and, indeed, at least as far as radio-active waste is concerned, that no migration at all is possible.

Great attention has been given in the UK recently to the monitoring of run-off from rubbish tips and the degree to which this affects surface streams and groundwater. This work has been carried out mainly by the Institute of Geological Sciences. Similar monitoring studies would be justified in and near large cities and industrial centres of developing countries. Unfortunately such research is expensive, long term and uses scarce skilled manpower.

In order to use poorer quality waters they can be treated to improve the quality or can be mixed with better waters up to the limits of acceptable quality whether it is for domestic use or for irrigation.

The only really effective treatment is to employ some of the desalinisation processes. Three processes are used currently - flash distillation, reverse osmosis and the use of de-ionising resins. The first is more appropriate to sea water and the last is not yet developed to the point where it is economic for large quantities. Reverse osmosis is normally used for groundwater and is much cheaper than any method used for sea water - providing the groundwater is much less saline than sea water. Thus we can expect that in the future, where the right conditions exist, saline groundwater will be used for desalination rather than sea water. Desalinised water may be as low in salts as 10 ppm and is often very corrosive and unpalatable. In order to use for domestic water, it is sometimes mixed with poor quality groundwater to increase the salt content and to help reduce the aggressive properties. This is being practised for the Riyadh water supply in Saudi Arabia, where considerable quantities of marginal groundwater are being used to mix with desalinised water. The use of a similar mixing process is being practised in some of the Gulf countries for agriculture but at about \$ $1/m^3$ there is no case economically for using desalinised water for this purpose.

The more usual case for irrigation is to use groundwater as a supplement to high quality surface water, or in the case where the groundwater is too saline it is then mixed with surface water before use. Where there is a real problem of poor quality water, mixing can be done by discharging wells into the larger canals (where the effect will be small) or by mixing at watercourse level. If wells are pumped into smaller channels above watercourse level, then, inevitably, the salinity of the canal water increases towards the tail. Let us suppose, for example, that a canal discharges four units of water at the head and diverts one unit at regular intervals along its length to watercourses and further receives one unit of water from wells just below each watercourse offtake. If the surface water has a salinity of 200 parts per million (ppm) and 2 000 ppm well water, then the increase in salinity in the channel is as shown below :-

Offtake	Upstream salinity (ppm)
Head	200
1	200
2	650
3	990
4	1 240
5	1 430

The mixed water in the channel rapidly becomes too saline for use, unless special practices are adopted.

Mixing at the watercourse generally involves some arrangement of weirs to try and ensure correct proportioning. Normally this is possible with 1:1 mixes but becomes difficult at two parts of surface water to one part of groundwater and at any greater ratio. The reason for this is that surface water is often restricted and fixed in quantity and thus at high mixing ratios the maximum discharge, which can be handled from a well, becomes rather small. As has been indicated earlier, such continuous mixing is not strictly required.

Provided that the crops grown can tolerate the salinity of the well water, a programme of alternate watering can be adopted to virtually any overall mixing pattern. This latter scheme is a much more practicable proposition for the farmer, provided that he can be made to understand the quality difference and the necessity for careful control.

The matter of aquifer management is touched on in the section of this paper comparing the problems involved in the private and public development options. There it is concluded that only the public sector can hope to manage the aquifer. And yet even at Government level the problem is still considerable. Institutions themselves are inadequately established and the legal framework is often non-existent or unenforceable. Within projects the position is sometimes a little better in that the Project Director may have sufficient knowledge and sufficient power to exercise some control, although he is often hampered by budgetary constraints. For example, by simple monitoring of the watertable level in an area where saline drainage wells are installed, a high order of management can be achieved. By intelligent operation the quality of the effluent and its disposal can be controlled.

Quality damage within extensive aquifer systems is not easy to achieve. In general, groundwater movement is very slow indeed. For example, in the Indus system the down-valley flow is of the order of one metre a year. The vertical transfer of water from one layer to another is also slow on a regional basis. Having said this, it is common for the quality from individual wells to deteriorate very quickly and for saline intrusion in coastal areas to become a severe problem. Recent studies in Bahrain highlight a particularly severe case of this kind of deterioration (MacDonald & Partners 1980).

It is doubtful whether aquifers are really managed effectively anywhere outside the western world, although some attempt is made after severe problems have been encountered. Then draconian measures are often adopted. For example, all new well construction is prohibited. However, the more recent deep wells still continue to be pumped and shallow wells continue to dry up.

There is another problem, identified elsewhere in this paper, that no two authorities even in the same country can agree on the ground rules. This is the case, particularly, with mining, or the degree of mining. Further, there is no universal agreement on quality acceptable for irrigation, although the WHO standards for drinking water are generally accepted.

Summarising, institutional aquifer management often does not work because of inadequacies of groundwater law, lack of enforcement where the law exists, disagreement on objectives, too many overlapping responsibilities between rival organisations, budgetary constraints, poor understanding of the problems, inadequate staffing and monitoring.

7.3 Data Requirements

A dozen years ago one of the authors (Stoner 1969) addressed the problem of data gathering and introduced the idea that a certain minimal amount could satisfy the needs of resource planning. The following quotation from that paper is as true today as it was then.

> "Experience teaches us to beware of massive data gathering programmes. Such programmes can be expansionist in their nature and obsessive in their demands upon the investigator's time, until merely collecting the data becomes an end in itself".

And yet we continue to gather data on a vast scale, much of it useless and all of it very expensive. The fault lies with those that set up terms of reference (TOR) for studies both within the Governments concerned and within the aid giving agencies. Normally TOR are circulated to the various departments concerned and often each feel obliged to add something whether needed or not. Really what is needed is for the TOR to be pruned severely so that only work directly concerned with the objectives of the study is requested. Here again there is a problem with poorly defined, or even contradictory, sets of objectives. Clear thinking at this stage can save time and money. All this is as true of groundwater development as it is of any other resource study. But in the case of groundwater, data gathering is even more expensive than for most other resources.

Ideally the planning process should proceed from reconnaissance to regional plan to project feasibility and on to implementation. Each stage should define the TOR for the next. When consultants are asked to submit proposals, they are often required to comment on the TOR but such comments are often ignored. The question should be firmly posed in invitations. 'How can these studies be reduced in time and extent and yet still meet the objectives?' In particular, 'Inception Reports' should be addressed to this problem and the utmost flexibility allowed in tailoring the TOR to the job in hand.

International standards are also at fault in that they have frequently been derived for Western conditions and have no relevance whatever to the deserts of Africa, the Middle East and the Indian sub-continent. This is particularly the case for soil and land capability surveys (Robertson and Stoner, 1970) where costs could be very substantially reduced by adopting standards and scales of mapping appropriate to local requirements. The whole subject requires a far reaching study on its own and is certainly too wide for this paper. A number of projects, which have involved the authors, would also be suitable case studies. Immediately the Lower Indus Project and the Khairpur Scheme in Pakistan and the Umm Er Radhuma Study in Saudi Arabia spring to mind.

If for a groundwater study a model is specified, then the quantity of data required goes up enormously. In the next section of this paper that deals with models this question is discussed and, in particular, the need for a model is questioned. If it cannot be avoided, the detailed knowledge of the aquifer thickness, permeability, leakance from overlying and underlying formations, piezometric levels, storage and recharge characteristics, pumping records and all spatial and temporal variations in these parameters are needed. Many of the groundwater schemes implemented in the past, before modelling was possible, have been very successful and, although the digital model is undoubtedly the most powerful analytical tool available to us nowadays, it is not always necessary or even desirable.

Some knowledge of water quality is essential and again this matter is dealt with elsewhere in this paper where international standards are questioned. Frequently quality varies both laterally and with depth and it is necessary to try and define limits so that the pumped water is suitable for the objective purpose.

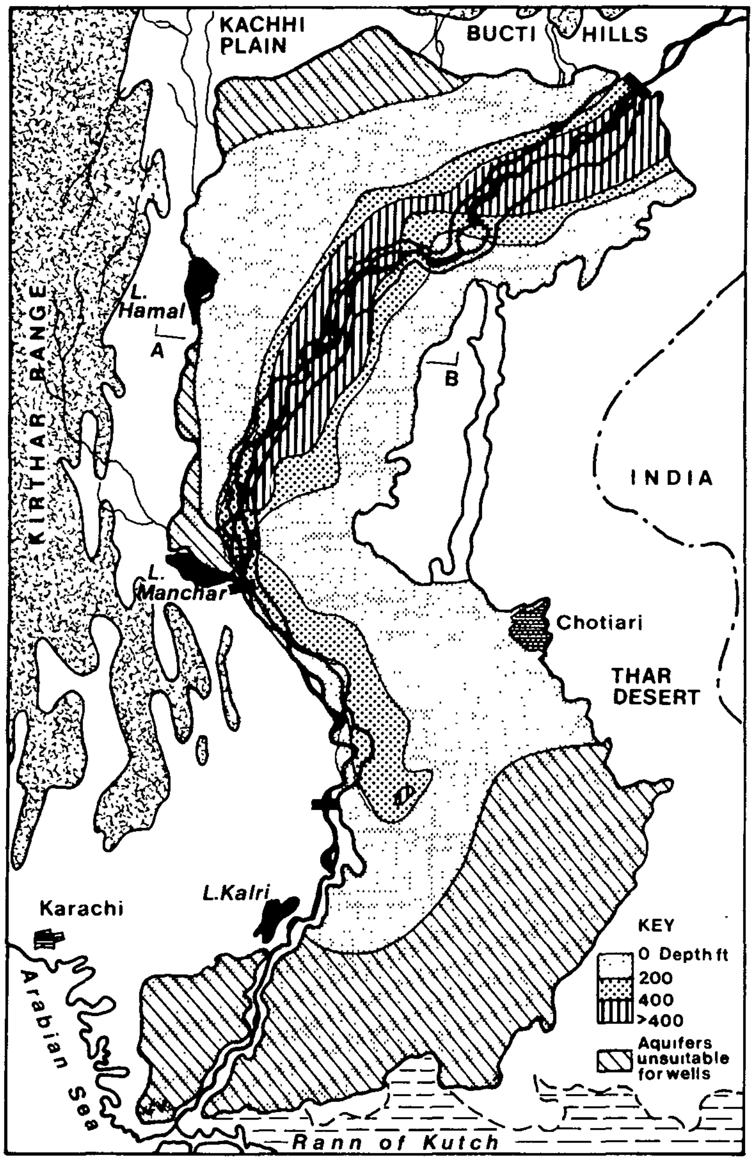
However, obtaining such information is costly and involves a programme of drilling boreholes and taking water samples at various depths. It is a matter of considerable judgement to define the location of such boreholes and sampling intervals to ensure adequate information. Figures 19 shows an outline map and a cross section for the Lower Indus valley in Pakistan and were derived from some 400 boreholes.

One principle in groundwater investigations is that, once it has been decided to drill boreholes, then the cost of obtaining data from them is comparatively small and thus it is all the more wonder that the data abstracted are often inadequate. Observations such as detailed lithology, geophysical logs, chemical analysis should be routine. More care is required in regard to pump tests which can become costly if long term tests are specified or if aquifer property testing involving drilling a number of nearby piezometers is required. Generally these can be avoided if a model is not required because often the most important information is the performance of the well. This may only require a step test which can be done conveniently in one day.

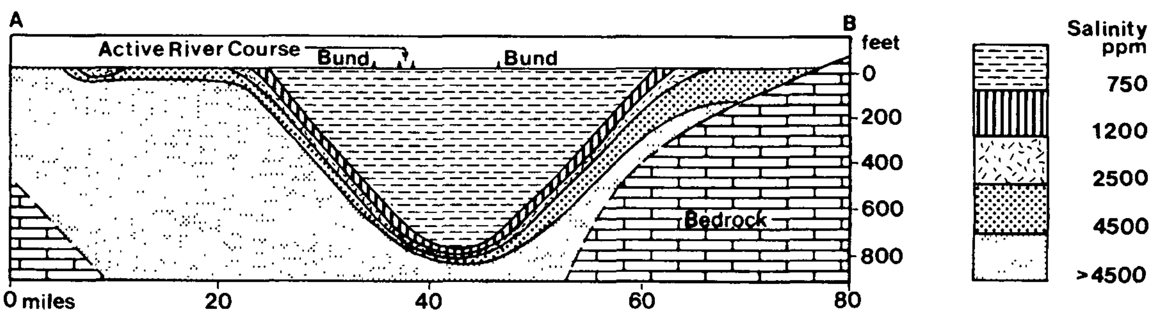
Beyond the implementation of the project there is a need for monitoring. Again we must beware of apparently endless data gathering and only collect that information which can and should be analysed. This would include the performance of the wells in terms of specific capacity and the quality of water produced.

It might also include systematic but selected soil sampling to determine whether the applied groundwater is affecting the land. Also the reaction of farmers to using the water requires monitoring. This work was done to good effect for some time on the Khairpur Tubewell Project.

FIGURE 19



GROUNDWATER QUALITY < 1200 ppm DEPTH CONTOURS



VALLEY CROSS SECTION

Concluding this section there are some clear indications for the future and some specific questions which should be asked and studies which should be made. First, data must be gathered to some identified hypothesis. The hope that random and extensive data collection will produce the hypothesis is false and expensive. We must ask what are the objectives; what answers are needed to meet these objectives; what analyses are going to be made to get these answers; what is the minimum quantity of data needed for such analyses. A certain flexibility is required so that changes in direction can be made if one trail is proved to be false. But above all, to return to the first point, there must be a system, a set of hypotheses, a plan. A generalised conceptual plan for a groundwater project is given in Figure 20 which shows how the elements of development fit together from concept through implementation to operation and maintenance.

7.4 Use of Models

Models are very much the current fashion whether they are appropriate or not. In some ways groundwater system models are like critical path analyses and other operations research techniques - excellent tools for understanding and defining a system just as long as you have the strength largely to ignore the answer. The main reason for this state of affairs is that the base data are often inadequate to construct even a sufficiently accurate representation of static physical systems. Historic records of water levels, recharge and discharge are in most circumstances woefully short of the standard needed to provide a reasonable simulation of the dynamic system.

The latter is possibly the more important in that it is only by demonstrating or validating the model to produce the present watertable level patterns (piezometry) using historic inputs and pumping data that we are able to use it as a predictive tool with confidence.

This is true of models generally whether physical or economic. If you cannot show that you can simulate history, then there is no possible reason for believing that you can predict the future.

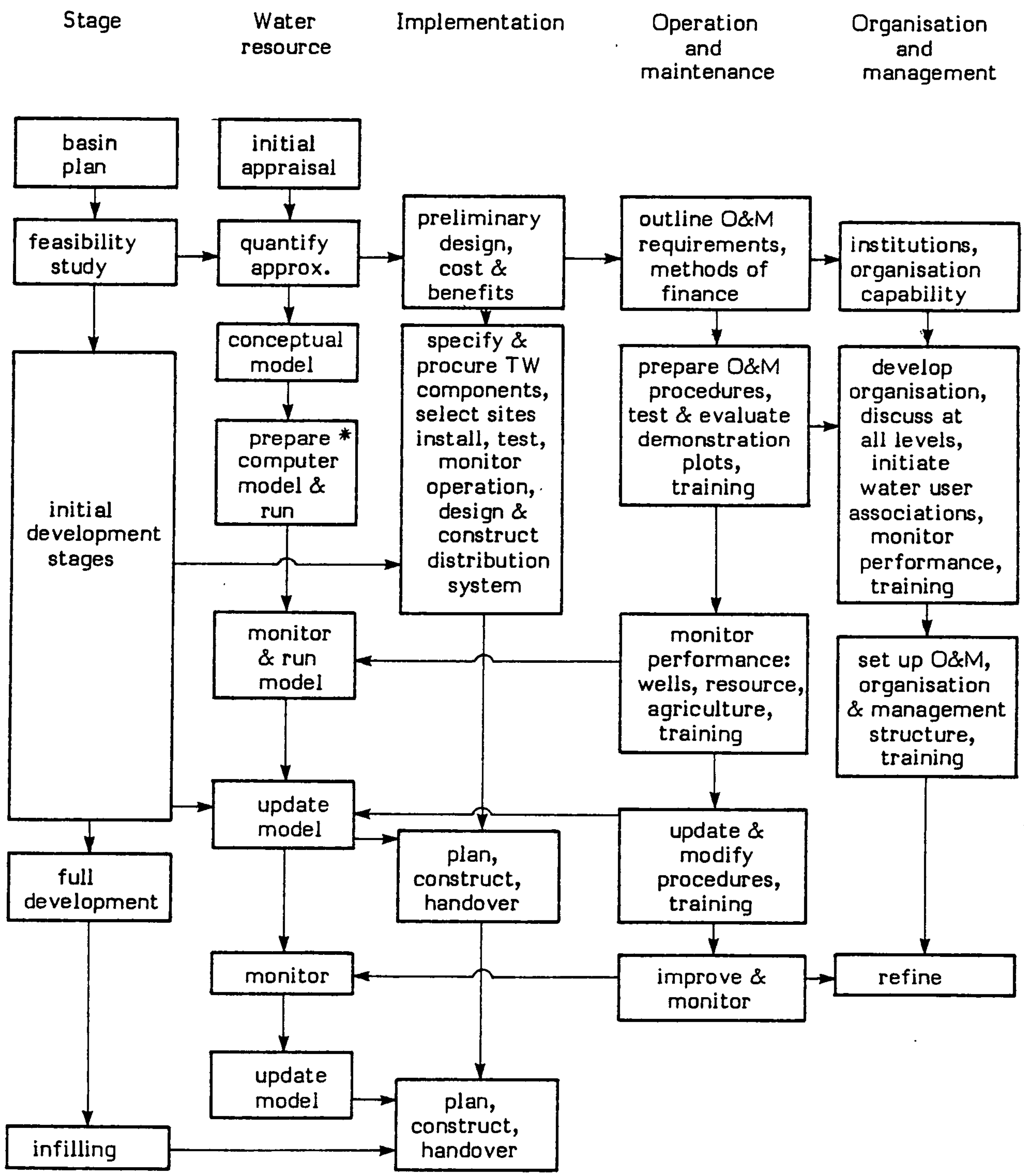
Where that data base is adequate and good simulation is achieved, a groundwater model is the most powerful analytical tool available.

In discussing models so far we are talking about digital models, either of the finite difference or finite element type. The former are the more popular and the more appropriate in that their set up involving flows to and from cellular polygons and storage within these cells does simulate in the mathematical sense the real working of the physical system. There are, however, other types of models which might be either hydraulic or analogue. Both of these types are useful in understanding flow systems and for demonstration purposes but they no longer have a place in practical analysis.

The assemblage of data required for the standard finite difference model can be enormous. If, for example, we look at one cell, Figure 21 specifies all the data required. Typically a model will have some hundreds of such cells and the similar data must be gathered or calculated for each. This formidable array of required information cannot be supplied in all cases and the cost of obtaining it is quite prohibitive. Even so, a model may be worthwhile because of the

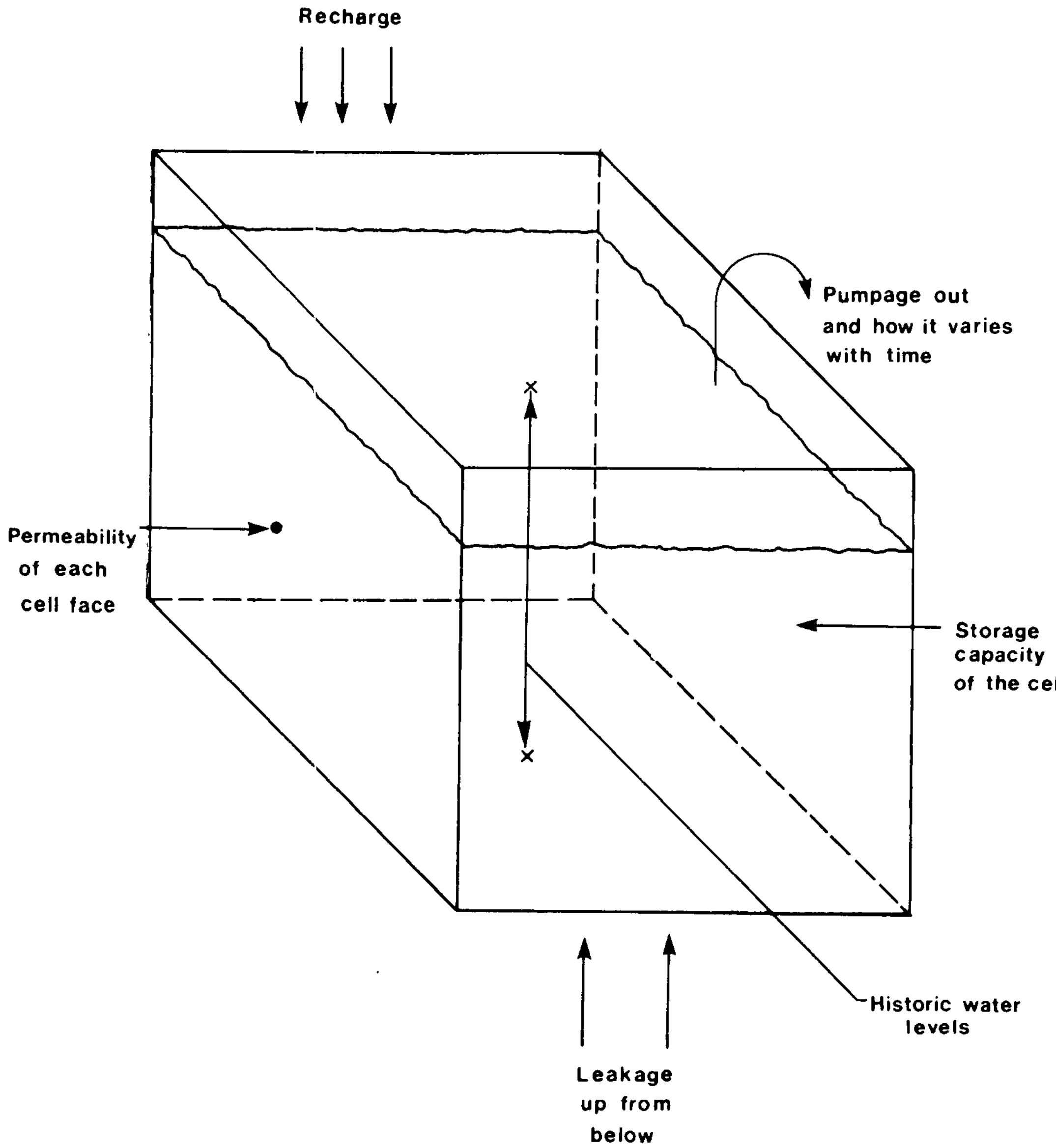
FIGURE 20

General Flow Chart for GW Development



* If appropriate

FIGURE 21



Recharge
Pumpage out
and how it varies
with time
Permeability
of each
cell face
Storage
capacity
of the cell
Historic water
levels
Leakage
up from
below

understanding of the flow system that the discipline of model construction demands, and the fact that, as further data are gathered, the model can be upgraded. Poor data should not be an excuse for sloppy analysis providing the value of the result is suitably qualified.

The use of a model for planning purposes depends on defining the objectives. Broadly, the main objective is to optimise the use of the resource. More specifically, this may involve pumping to balance recharge; it may also involve a restriction to avoid drying up existing wells; it would almost certainly require the prevention of excessive drawdown in the more intensively developed parts of the aquifer. Alternatively, some degree of controlled mining might be allowed. All of these conditions can be met by examining various configurations of wells and applying appropriate economic controls so that undesirable developments are avoided.

Further complications arise when a conjunctive use model is involved and an optimum use pattern between surface and groundwater supplies is demanded. It becomes even more complex if surface storage is contemplated. It may then be necessary to run the model using historic inputs and try out a series of possible construction options (for example, the size of a storage reservoir) together with a number of possible management options to try and get the best out of the combined system.

Earlier we described the usual model as partial, deterministic and static whereas the prototype is stochastic and dynamic. A simple illustration will demonstrate the kind of problem which can arise from this basic misconception. In the late sixties a model was made of the Indus Basin which involved the conjunctive use of surface water, storage, rainfall and groundwater as inputs and evaporation and evapo-transpiration, system losses and river outflow as outputs. This model uses fixed values for precipitation, evaporation and evapo-transpiration based on probabilistic analyses and then is run with various actual years of river flow to determine what levels of irrigation demand can be met. The fallacy of the method is that rainfall, evaporation and river flow are all part of the same hydrologic cycle and cannot be treated as completely independent variables. By the adopted method the total hydrologic event put into the model has no known probability. It is much better in these circumstances to run the model with all the hydrologic inputs as variables and to assign the objectives certain achievement probabilities. Thus, for example, if we wish to determine the area which can be irrigated in, say, four years out of five, we can use this as the objective criterion and derive the required area by running the model with a run of actual records. The model is then fully stochastic and meaningful probabilities are derived for any given set of objectives. These could involve the need for and size of surface storages, the degree of flood protection provided and for the use of groundwater as a base or as a peak requirement.

Economists will recognise that the complex real world of integrated surface and groundwater irrigation, with numerous cropping options and various resource constraints, is amenable to modelling by linear and other forms of mathematical programming analysis. Such an approach would enable analysts to explore the merits of alternative projects and various specifications. It should indicate crucial and weak points in the data, enable tests of alternative design criteria to be carried out and indicate the policy implications of alternative objective functions. This was shown to be technically feasible by the work of Smith and others in the Harvard Water Programme more than a decade ago. Smith (1970) aimed to ensure model development which 'does not seriously violate economic or technical reality, that assumptions are clearly enunciated, that sensitivity analysis can be readily performed, that readily available data are used efficiently, and that efficient, well known techniques are employed to provide the fundamental computational kernel'. He illustrated the approach with data from what was then East Pakistan and derived both deterministic and stochastic models.

Very little progress in applying these techniques has been made in the developing countries since that time. It is extremely rare for planning authorities to use mathematical programming techniques for anything other than investigation of the hydraulic potential of the aquifer. It is worth speculating on the reasons for this :

(i) the real-world problems are proving to be more complex than even the most refined models. Specification of a comprehensive model requires inputs from several disciplines and the unsatisfactory outcome of many modelling exercises may be attributable to the inherent difficulty of incorporating all the system components and of obtaining an appropriate balance of components as well as valid data. Seldom do all the specialists fully understand the workings of the model and therefore they will either accept the working of the model uncritically or reject it out of hand. Specification of socio-economic aspects of the integrated system has inevitably been particularly poor;

(ii) the technical capacity to construct models and software is not readily available in poor countries;

(iii) the computers and other hardware are not available or not reliable enough to service the tight timetables of planning groups;

(iv) leaders of traditional planning teams have often failed to keep abreast of developments in computer modelling and are sceptical or even hostile to their use. The modellers are not always effective communicators of their art.

ANNEX I

An Analytical Framework and Agenda for Future Research

The variables, which enter a theory of rural development, of which those concerning groundwater development comprise a sub-set, are well established. But the relationships between them, particularly the dynamics of social change as it affects and is affected by groundwater development, are extremely vague. Identification of key structural variables and their interactions within the groundwater development systems and with general rural development should be the first aim of any detailed studies. In the ideal analytical framework instrument variables, which will enable manipulation of the system, need specification and the effect of any changes predicted.

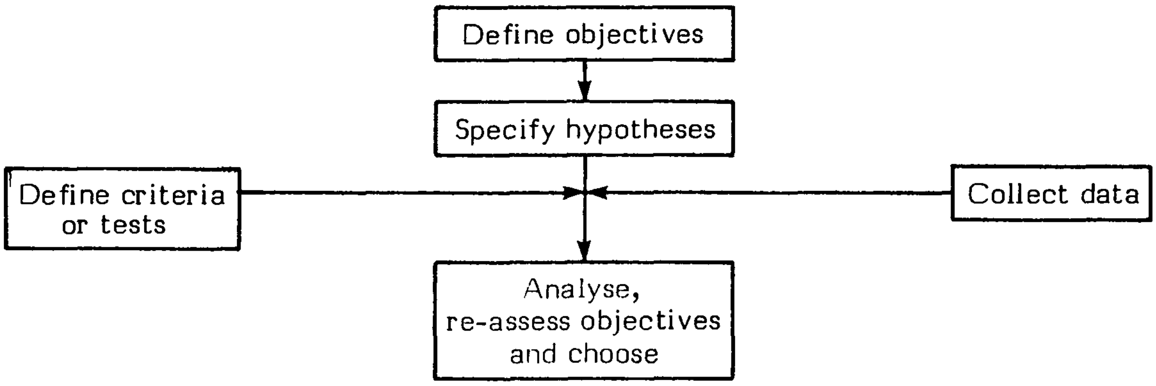
Groundwater projects have various, often multiple, objectives. It is possible to categorise projects according to their goals:-

- maximum agricultural production;
- maximum return to public (or private) investment;
- employment creation;
- etc.

Seldom are objectives set out in this way and almost never is any weighting given. In the case of private farmers, objectives are a matter of research, debate and controversy. In principle, complex weighting procedures are possible but, in practice, one objective - say, rate of return to investment - is maximised subject to minimum performance levels with other goals.

Project level objectives are seldom specified by those familiar with the major sector problems and resource requirements and availabilities. This study was intended to assist those involved with groundwater to set (or appraise) reasonable, realistic objectives. General goals, such as 'maximise employment creation', need decomposing into operational targets. This requires effective communication between politicians, adminstrators and technical experts. Issues papers such as this have an important role in the process of disaggregated or target objective setting.

It is easy to regard the hypothesis as the basis or rationale for the target. However, they cannot aid planning of the detailed components until operationalised by criteria or tests of preferedness. Here is a weak link in many planning exercises. General criteria of the form 'line canals if net present value to farmers of water saved exceeds the net present value of costs incurred - all measured in efficiency prices' are often not made explicit. Where they are defined there are often problems of data availability and quality which preclude selection of targets, design decisions or other policy issues on the basis of the test set. We hope that the bald format of our conclusions will stimulate scientific testing of groundwater development options and more sensitive assessment of problems and opportunities which arise.



There are several categories of hypotheses which must be specified including technical, economic, financial, administrative, social, legal and political categories. The selected hypotheses should be testable by empirical procedures or at least assessable by reference to theory or logic. Whilst behaviour of groundwater in an aquifer will be subject to the laws of a robust theory, once the water is lifted it is part of the more complex social system. Here theory is much weaker, events less predictable and much of importance is not understood. Water use will be influenced by such matters as the size of the country, its political philosophy and traditions, the level and form of development, the scarcity value of water and many other issues. Therefore general conclusions from research will be hard to defend in the light of divergent circumstances. Nevertheless we believe that a certain degree of technological determinism can be sustained. We have therefore set out some provocative hypotheses which are judged worth accepting or testing. They are set out in plain English with no formality and then are elaborated in the body of the report. The reaction of knowledgeable practitioners, with a wider range of experience than the writers, plus detailed case studies and ex-post evaluations may help alleviate the major anticipated problems of either over-development or under-development of groundwater, increasing salinisation, inappropriate technology and institutional control, inequitable access to a profitable resource, and inadequate operation, maintenance and management.

Technical (Engineering)

Mechanically powered wells are preferable to hand-or animal-powered wells in almost all circumstances, from whatever viewpoint. Tubewells are a better investment than open wells. Over time, drainage will become increasingly important where operating problems exist. In time, mining will become a problem where fresh groundwater exists. Excessive data requirements are often specified but recording (especially lithology) and access to the data is poor. Frequently a great deal is spent on drilling test wells and relatively inexpensive testing and analysis is inadequate. Recent advances in groundwater simulation models (excluding economic and social aspects) have increased our capacity to predict aquifer behaviour under alternative development patterns. There are shortages of skilled manpower in some countries and generally too narrow a disciplinary focus.

Coping with saline disposal, including mixing, is a problem. The risk of pollution of aquifers with salt water and industrial waste is increasing. Appropriate wellfield design and pumping regimes can help prevent saline water intrusion. Revised water quality guidelines and the related watering regimes are urgently required. Saline water (greater than 1 500 ppm) should probably be developed publicly.

Technology packages should be compared on the basis of field operating experience, not on potential efficiency. There has been no rigorous test of the hypothesis that low cost wells are inferior from a hydraulic, engineering and financial viewpoint. Economies of scale in well costs are more apparent than real. Labour-intensive construction is slower than alternatives. It is more economical to redrill an encrusted well than to attempt to rehabilitate it.

Centrifugal pumps are a better proposition than any other where they can be used. Electrically powered wells are much preferred by farmers and operating agencies.

Economic

Net benefits are greater when rainfall or surface irrigation is augmented. Poor canal operation and maintenance creates opportunities for privately profitable groundwater development. Additional water from public tubewells creates a unique opportunity for surface irrigation reform. The benefits from public regulation of groundwater will increase over time. Studies of seasonal opportunity costs of water shortage and of the value of critical water will aid unrestrained planning. Designs of public schemes to incorporate advanced multi-purpose benefits, such as design for either load shedding or maximum hydro-electric power, are needed. Integra-tion of technical engineering and socio-economic models to produce decision models has not advanced beyond the research phase.

The effect of discount rate choice (or IRDR) upon technology choice requires further research. Mining generally pays. Rehabilitation projects are the most economic type. Private development is rapid and efficient until abstraction exceeds recharge. Economic (not financial) assessments of alternative power, pumps, screen and disposal systems in different countries are required to aid technology choice. Funding of O & M can yield large returns.

Legal

Absence, or lack of enforcement, of a suitable legal framework precludes crucial public policy initiatives. For example, without legal sanction (or financial subsidy) socially uneconomic mining cannot be stopped. A legal framework to ensure reasonable access for all beneficiaries can be devised. Legal frameworks derived from temperate countries (for example, Britain) will prove inappropriate in arid areas. Preparation and implementation of the law lags behind need.

A single legal entity responsible for surface and groundwater is desirable but, failing this, there should only be one body co-ordinating groundwater development.

Political

Lack of determination to apply legal sanctions creates sub-optimal and inequitable development. The costs of limits to government power are not acknowledged. The various real objectives of government are not well specified and the separate and varied objectives of institutions and individuals not recognised. Some frankly political objectives are inappropriate to groundwater development. Aid for foreign capital but not local costs or recurrent costs favours sophisticated capital intensive technology. Rehabilitation is not the easiest project to get aid funded. The opportunity is passing for conserving groundwater for the benefit of poor people. Once mechanically powered pumping is introduced to a region, manual pumping and, eventually, animal-powered pumping will become either uneconomic or unfeasible. Groundwater is not a good area to pursue either real or illusory income distribution policies.

Financial

Financial returns to public projects are minimal and could be enhanced. Recurrent funds are inadequate. Short and medium term credit for private farmers is deficient. Rehabilitation projects are the cheapest. Financial returns from co-operatives are at a lower rate than those from independent farmers. Private farmers have high operating efficiency and make high profits particularly when credit, capital and fuel are subsidised. Private development saves public investment.

Administration

O & M on public projects is poor and deteriorating. Too many agencies are involved with groundwater.

Successful management of integrated surface, irrigation and groundwater systems need analysis and publicity.

Administration capability is the single largest constraint to project implementation and performance.

Governments can, in principle, manage aquifers but not efficiently operate wells. Private owners operate wells and distribution of water efficiently but cannot do so in a way that optimises wellfield social benefits.

Social

Local monopoly of private groundwater leads to exploitation of weaker/smaller farmers. Independent power from diesel/electric engines is employment replacing but tubewells are employment creating. Low-cost, simple technology generates local employment and, whilst hydraulically inferior, deserves support on this count in many cases. Fragmentation of holdings impedes private development.

Sociological research is needed on the links between technology, land income and wealth creation, the relative importance of exploitative relationships and levelling mechanisms within the social fabric.

The factors required for successful co-operative formation needs study.

Technical (Agriculture)

Profitable cropping patterns have peak demands; canal supply often cannot match these needs. Empirical measures of the effect of alternative levels of saline and fresh groundwater on crops are lacking. Groundwater is most profitable when supplementing other water sources.

Soils problems have often been over-emphasised in respect of using saline water.

The need for drainage is well established but the implementation record is abysmal.

ACKNOWLEDGEMENTS

We would like to acknowledge the useful comments and suggestions from several colleagues including Mike Barber, Alison Burrell, Ed Clay, Clive Collins, Bhupendra Desa, George Gwyer, Fred Hotes, Mike Nelson and Alfredo Steir-Younis. They helped us to clear up some of the problems. Many remain, some may be insolvable!

Ian Halse, John Sykes and the staff of the Library and in the Word Processing Department of Sir M. MacDonald & Partners greatly assisted us in report presentation and in preparing the bibliography.

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The groundwater development literature is scattered, touches a wide range of subjects and the bulk is in report form and not published in recognised journals. A computer search was made using the Common Agricultural Bureau (CAB Abstracts) and US National Agricultural Library (Agricola) data base. Key words included groundwater, tubewell, developing countries, management or planning projects.

This search was not very successful. This is partly due to the bewildering mixture of terms adopted from geology, physics, engineering mathematics, agriculture, economics and other social science disciplines. Much of the key material is not published but it is in mimeographed form - what is sometimes termed 'fugitive literature'. Some 55 references were produced but only seven were new to the authors. Over two hundred references are included in the following bibliography, the majority of which are readily available.

Readers are invited to supply supplementary reference lists which can be incorporated into a final version.

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