IRRIGATION MANAGEMENT NETWORK

CONJUNCTIVE WATER USE FOR IRRIGATION: GOOD THEORY, POOR PRACTICE

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Network Paper 4

October 1991

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CONJUNCTIVE WATER USE FOR IRRIGATION: GOOD THEORY, POOR PRACTICE

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1. INTRODUCTION

As frontiers for new irrigation development become fewer, and the demand to produce more food increases, so does the need to use resources more efficiently, and operate existing irrigation schemes more productively.

Conjunctive use is the combined and integrated management of surface and groundwater for optimal productive and allocative efficiency. At farm- or scheme-level conjunctive use is the concern of farmers and scheme managers attempting to optimise the quantity, timing and reliability of supply and maintain soil fertility over the year. At regional level the combined management of the resource is of interest to planners and water resource engineers seeking to maximise water availability, and increase the quantity and sustainability of supply in the longer term. Ideally conjunctive use of resources extends the utility of available resources, and should not be used to describe the development of one resource simply to hide shortcomings in the provision of the other resource. However, conjunctive use on irrigation schemes is often a system of 'joint use' where groundwater has developed for a variety of objectives, particulary to deal with waterlogging problems, or to compensate for failure in the surface water distribution system. Joint use has also emerged as a result of the spread of well technology outside of any specific operational programme organised by water management institutions.

This article reports the result of a literature survey of conjunctive water use. We looked at the breadth of existing literature, the contexts in which research was performed, the models built to analyse options, and the use of research to inform policy options (or the failure to use research constructively). By looking more at the various objectives behind the current interest in conjunctive use, we hoped that we could make some recommendations on research approaches. In this paper we look first at the diversity of objectives behind current interests to promote conjunctive use, and how this has affected the development of coherent research to inform policy. We then look briefly at the hydrology of conjunctive use, and some of the hydrological and rural planning models constructed to inform policy and implementation initiatives, with a longer overview of models provided in Appendix 2. Finally we look for at the use of institutional analysis as a means of organising research on conjunctive water use, and as a means for looking at the solution of multiple objectives in conjunctive use.

Conjunctive water use has been a water resource development tool since to 1960s. Concerns over the technical mobilisation of more water have shifted into serious considerations on water allocation as water resources are seen to be reaching finite limits. It has also been of specific interest in many regional rural development plans over the same period (see Biggs, 1974; Rogers and Smith, 1970). It has also become of increasing interest in irrigation scheme management. Conjunctive use became a component of World Bank irrigation development policy in the early 1980s, in response to increases in agricultural production of up to 20% witnessed in Pakistan (O'Mara 1984). It is claimed conjunctive use can contribute to improved agricultural performance, sustainability and equity (Prasad and Verdhen, 1990; Dhawan, 1988). An improved water supply can increase output by facilitating the irrigation of additional land and permitting increased irrigation intensities. It can also support changes in cropping patterns, especially crops with heavy water demands like rice and sugar cane, or cropping patterns which allow farmers to optimise their combinations of rainfed and irrigated crops. The reduced uncertainty of poor or irregular supply from surface water and allows farmers to risks investments in water-intensive and higher value crops, HYV seeds, and associated inputs like fertiliser and pesticides.

We found an historical analysis of research was important. Much of the analysis from the 1960s and 1970s proved to be highly relevant to some current dilemmas on research and policy formulation. Much of this literature pre-dates computerised abstracts, and is also linked to earlier research paradigms which predate the current focus on local water management institutions. As a result much work had almost disappeared from 'corporate memory'. We may talk much about the essential importance of farmer knowledge, but this literature review showed up the importance of using the knowledge of engineers and social scientists prepared to spend time not only recalling past work, but also evaluating it.

According to the World Bank (O'Mara, 1984), conjunctive use should be equitable or at least 'Pareto safe', i.e. no irrigator should be worse off, and

the gap between richer and poorer farmers should not be widened. Irrigators should have access to one or other resource and there should be compensation where there are proportionately greater gains from one or other resource. Further, O'Mara suggests that variability in supply should not effect users inequitably, and rights should apply to all sources equally, i.e. they should not differ between surface water and groundwater. This is difficult to achieve in practice. While similar types of rights may make for easier control, there is no reason to expect changes would be culturally acceptable in all societies. Surface water and groundwater development have profoundly different needs in communal and 'supra-community' action, and we should not be surprised that it is very difficult to develop similar rights of access, ownership and control.

We found a great deal of confusion in the literature, with the reports on the diversity of circumstances of conjunctive water use threatening to overwhelm any systematic analysis of research needs, or systematic debate of institutional needs. We now know quite a lot, and certainly are speculating a lot, about the effects of joint use on farmers and tertiary level water management. However, we know very little about how farmers and bureaucrats are actually acting to ensure that risks in decision-making over the use of resources are reduced. At the regional level, we see few directives to ensure the production of useable technical documents, or to encourage a cadre of staff capable of debating technical and- political recommendations, and transferring these into practical procedures to encourage conjunctive use.

One key source of confusion is the call for conjunctive use developments to serve more than one set of objectives. Research, however, has not always been designed to provide information for diverse objectives, and thus the resulting recommendations are abstract or politically infeasible. We also found it useful to distinguish studies which really were actually looking at the institutional prospects for joint use of water, and those studies looking at problems in technical innovation and the adoption of well technology. As we discuss later, these are actually very different initiatives, and great confusion has developed in the literature in the expectation that water management agencies should somehow encompass or organise all initiatives relating to changing the production of irrigated crops. Few authors have looked systematically at the scope for different institutions to evolve, and/or collaborate to meet different needs. Thus recommendations from research were not linked to a forum where recommendations could be debated.

We found many environmental models, a number of economic models, and several articles involved in descriptions of the utility of different models for different kinds of problems. Some modelling work has been well developed. However, many of the models are very abstract, and often have a very weak summary of the actual schemes they are supposed to serve and rarely consider the decision-makers supposed to use the recommendations. In fact, we have found no examples in irrigation where the utility of mathematical modelling has been subsequently assessed as a policy tool, although this issue has been debated in water resources planning (see IASH, 1989). In the literature there are no critiques of policy on conjunctive use to show how institutional development has interlinked with research and technology dissemination to achieve the existing levels of conjunctive use, or how better levels of conjunctive water use might be achieved (although summaries of administration exist [O'Mara, 1988], and such studies do exist in other areas of water management [Clay, 1974; Sexton, 1991]).

Our review of models suggested that many were constructed for fairly clear objectives, although some criticism is possible for the limitations of equations constructed and quality of data used. However, there is some tendency for models built for one purpose to be used subsequently to answer other purposes, as well as to be transferred regionally without very close attention to hydrological and economic differences. For example, field experience suggests that theoretical models and software of hydrological interactions are used rather uncritically. Palanasami (1991) has recommended a specific well assistance programme to promote conjunctive use. However, the model he uses to justify this recommendation was designed to show costs and benefits of rehabilitation options at the scheme level, and has very little detailed groundwater information in it.

Both hydrological and economic models were unable to operate at the 'local' scale (usually the most disaggregated level is the region or scheme). Hydrological models had particular problems in modelling the behaviour of dug wells (rather than tubewells), seepage and drainage (and how this manifested itself in space and time), and metamorphic or 'hardrock' geologies (rather than alluvial and sedimentary formations). Most 'economic' models were actually involved in looking at returns to technical investments either to maximise food production or to look at rehabilitation, and rarely interpreted these options in institutional terms. No models currently exist that study issues of equity and rural transformation below the scheme level. Thus modelling, although useful for some studies in conjunctive water use studies, either cannot help us with situations with

complex objectives, or must be clearly subsidiary to other forms of research as a basis for reform of agricultural policy and water management.

This review has been undertaken by two authors who are essentially hydrologists with interdisciplinary training and full experience in development studies. Our review suggested a need for major improvements in research methods if they are to inform policy development. We found that improved institutional analysis and understanding was vital if more conjunctive water use is to be achieved. Please bear with us if we do not use the terminology developed by those more deeply involved in studies of organisations and public policy.

2. OBJECTIVES IN CONJUNCTIVE WATER USE

If we look at the objectives behind the promotion of conjunctive water use, the term first developed as a resource management objective to maximise water availability. However, 'joint use' of resources has also emerged as a technical option for a number of other objectives in irrigation management. These other objectives include:

- objectives on improved availability of water;
- environmental objectives to reduce waterlogging and salinity;
- production, equity and poverty alleviation objectives;
- fiscal objectives to optimise expenditure on rehabilitation;
- state disengagement from canal irrigation management.

With these other objectives, the system of joint use rarely maximises the physical availability of water - indeed, it may be tending to bring technical changes that fracture existing management institutions. However, the resulting pattern of water use may be optimal in economic, social or political terms.

Understanding these different objectives in conjunctive use, and how they have changed as a focus of irrigation research over time, is important since each tends to use rather different research methodologies and draw on different bodies of available information (and, in turn, ignore bodies of research).

A study of the literature on conjunctive use in irrigation showed a number of confusions in setting objectives, designing related research, and directing recommendations. Firstly, many authors expected more than one objective to be achieved by reforms. For example, some authors expected institutions to promote well irrigation in surface water schemes for equity reasons, but they also wanted to see maximisation of available water resources as well. Recommendations could be directed at institutions with very limited interests or influence in promoting well irrigation, or related support services. Secondly, researchers failed to consider how their research was informing the policy debate. Some researchers were indeed undertaking research linked to clear objectives, with prospects for their research to be linked to policy formulation. Many researchers, however, were undertaking research of topics that interested them, without seeing how findings could be linked to practical recommendations, and thus were making recommendations into a void. Thirdly (and following from this earlier point), authors thought they were doing research relevant to conjunctive use, where actually their results related to different issues (especially technical innovation in the use of wells, and the operation of water markets). One problem which is emerging is the expectation that all kinds of issues can be resolved within the 'water management' paradigm, whereas we may need to be looking at a variety of research themes, determined by a combination of institutions involved with rural development and water management.

In fact, we do not feel that research has yet been critiqued in terms of objectives and institutions. Instead, we find research directed in three areas:

- defining options for technical developments (here technology itself emerges as the objective);
- production and equity issues;
- concerns at technical innovation in groundwater use.

We now provide an overview of ideas in each of these three areas. In each section we review the weaknesses of approach, and try to show additional institutional studies which would be useful.

3. STUDIES ON TECHNICAL OPTIONS FOR IMPROVED WATER AVAILABILITY AND ENVIRONMENTAL MANAGEMENT

Although in theory conjunctive use may be planned from the outset, most planned irrigation initiatives have evolved over time for other objectives. One rare example of planned conjunctive use is the Yucheng Experimental

District in China (Ren Hongzun, 1990). Development of surface and groundwater resources have been combined with land levelling, soil improvement, forestry, and farmer management for an integrated irrigation and drainage system. The conjunctive water use component comprises a six level canal drainage and irrigation system which keeps water tables low in the flood season and stores water at other times, and a network of 1050 wells, 50 -100 m deep, to increase the depth to watertables and supplement supply. The results have been massive reductions in areas suffering salinity between 1949 and 1984. There have also been large increases in grain yields.

Quite a lot of literature exists purely to summarise technological options. Wells (usually tubewells, but sometimes dug wells) may be introduced to: (1) supplement inadequate canal supply, or provide an alternative source of irrigation water should canal supply fail; (2) provide vertical drainage to mitigate salinisation and waterlogging; or (3) mix groundwater and canal waters of different qualities to provide water of acceptable overall quality. A typical list of technology options is shown in Table 1 (from Khepar, 1990).

Supplementary groundwater irrigation may be introduced where canal supplies are inadequate, either for design or operation reasons, or where crops production practices have changes. Groundwater development in some areas may enable the areal extent of an irrigation scheme to be increased. Groundwater development may also proceed spontaneously, where farmers are outside the canal command, where users are dissatisfied with surface water provision, where groundwater irrigation is more economic, or where development of groundwater markets provide a good return to investment.

In some of the larger schemes in Pakistan and China, inadequate horizontal drainage and profligate water use have caused waterlogging and salinity problems. Over-watering increases salts deposited at the surface, and the increase in water infiltrating to groundwater causes the watertable to rise, increasing the concentration of salts in the rooting zone due to capillary rise. Tubewells were introduced in the 1960s and 1970s to provide vertical drainage and increase the depth to water table, and some of the less brackish water is diverted for irrigation. In Pakistan, tubewells were introduced under public programmes like SCARP I & II (Salinity Control and Reclamation Project) to provide vertical drainage to offset waterlogging and salinity problems caused by rising watertables from canal irrigation.

Table 1: Conjunctive use is planned and practised with the following objectives:

(i) Mitigating the effect of the shortage in canal water supplies often subject to steep variation in river flow during different periods in the year.

(ii) Increasing the dependability of existing water supplies.

(iii) Alleviating the problems of high water table and salinity resulting from introduction of canal irrigation.

(iv) Facilitating the use of high salinity ground waters which cannot otherwise be used without appropriate dilution.

(v) Storing water in ground water basins closer to the users, to ensure water supply to the users in case of interruption of surface water supply.

The various systems of conjunctive use may include the following:

(i) Augmentation of canal water supplies by pumping ground water through deep tubewells along the canal system as has been done in Punjab and Haryana.

(ii) Direct application of ground water in rotation with canal water through deep or shallow tubewells.

(iii) Mixing of saline water pumping through tubewells along the water course/distributories.

(iv) Reuse of drainage waters which may be good or of poor quality in rotation with surface water.

(v) Storage of rain-water in farm ponds, big depressions and lakes and its use in conjunction with canal or ground water.

(vi) Artificial recharge of ground water from supplies, run-off and subsequent use with surface water.

(from Khepar, 1990)

By example, private tubewells for irrigation have since proliferated rapidly, from 6,000 in 1961 to 190,000 in 1985 (Johnson 1989). Similarly, in China, conjunctive use was introduced as one of several rehabilitation measures to address waterlogging and salinity, high siltation rates in irrigation and drainage systems, and to provide a supplementary supply in drought years.

Chadha (in AIT, 1990) describes a typical transition from surface water to conjunctive use in Punjab, India. High irrigation demand has caused problems of inadequate surface water supply, waterlogging due to poor drainage (impeding clay layers), and widespread tubewell proliferation has led to the depletion of near surface aquifers. Augmentation tubewells are recommended which draw water from deeper aquifers (>60 m) to relieve stress on shallow aquifers, and provide higher quality drinking water near cities.

Poor quality surface water (high silt load) may be mixed with higher quality groundwater to provide a satisfactory overall quality, for example in China (Lou Puli, 1988). Alternatively in Egypt, mineral rich groundwater may be blended with better quality surface water (Scott, 1984). This may involve tubewells discharging directly into the surface water canal network, they may be placed adjacent to canals to recycle silty canal water, or tubewells may have their own distribution canal network consisting of temporary bunds managed and maintained by individual farmers.

Khepar goes on to note that choice of management is 'location specific', and then to look at research options in terms of better information on resource behave, and options in the use of models both for portraying the behaviour of resource and for the subsequent allocation of resources. Such an approach, where both institutions and water users are invisible, is a not uncommon approach to studies of the technical options to improve conjunctive water use. However, this framework is not that helpful for examining a policy framework for promoting improved conjunctive use, for a variety of reasons.

There are in fact, some important management distinctions which do enable comparison across very different kinds of technical options and which need to be understood for effective decision-making. The operational structure of the management institutions may indeed be very different in particular locations, but their form may not be. We can use an institutional analysis across the different technologies to see the functions of various institutions involved:

- Their existing and potential form (e.g. whether they are local, public, based in operations, based in collaboration with economic incentives etc). A fuller overview of institutional needs is given at the start of Section 6;

- How they should link together, to obtain both the 'joint use' needed for the particular exercise, and also to promote more optimal water allocation;

- Necessary development in procedures (changes, new developments);

Institutional analysis also tells us something about decision-making processes, especially whether groups of the *same level* of power are involved in the decision process, or whether organisations are in a *hierarchical* set of relationships (Schultz, 1989).

Secondly, such an approach fails to look at the different operational causes to existing problems in resource availability, both in terms of their nature and the institution with responsibility. This avoids analysis of some of the key current institutional issues creating uncertainty in the resource management environment. For example, simply providing new groundwater technology does make the technology adoptable, since the ongoing uncertainty of provision of surface water continues to influence both the hydrological environment and the risks to investment.

We can also see how limitations have emerged in both technical studies and organisation studies as a result of weak institutional analysis in many existing studies.

Where problems have emerged with waterlogging and salinity, there is often reasonable technical collaboration between research on groundwater and surface water management, for practical political reasons. On schemes where interest has developed in the shortfall of surface water supplies, information on groundwater is sadly lacking. Sometimes this may be a result of the bias of surface water irrigation bureaucracies, but it can also stem from other institutional problems. For example, much groundwater information in the state sector tends to come from wells dug for rural development reasons, which are often outside 'privileged' irrigation commands. Information in the private sector is difficult to coordinate. Many small tank schemes have never really been integrated into data

collection systems of surface or groundwater bureaucracies. Hence available data is not coordinated, and it is difficult to organise new data sources.

As a result of institutional uncertainties (especially on the remit of state groundwater institutions), much research on operational constraints on water availability has been led largely by social scientists. They can tend to make assumptions on the 'automatic' availability of groundwater in irrigation schemes, whereas actually groundwater may be in limited supply, of poor quality, and expensive to develop because of depth to water table. This tends to happen particularly in smaller schemes in broken topography where aquifers are poor. Social scientists frequently (and rightly) call for better groundwater information, but we do not get any systematic review of the complexities faced in making this happen. This not just bureaucratic competition - surface and groundwater bureaucracies often understand the problems - but they are not trained or equipped to take on additional work. Difficulties may include the limited manpower and equipment of many groundwater institutions: headquarters of different bureaucracies may be far apart; also there may be no formal structure to bring surface water, groundwater and rural development staff together for discussion.

4. EQUITY ISSUES AND SUPPORT NEEDS IN JOINT USE

A lot of research work looks at the prospects of groundwater to reduce inequities of water distribution, and increase cropping intensities and crop yields to increase incomes in irrigation commands. The introduction of groundwater irrigation promises to smooth out peaks in demand and troughs in supply associated with canal irrigation (Chancellor-Weale, 1989). Dhawan (1988) makes a very strong case for the joint development of groundwater in surface commands.

Within the debate on conjunctive use within irrigation schemes, most attention has focused on the development of groundwater in areas irrigated by surface canals. Research covers both schemes where surface water is managed by state agencies, as well as smaller schemes organised through indigenous institutions.

However, conjunctive use does not always bring benefits and can be problematic. It is likely to disrupt surface water management practices or at least require its reorganisation. This might include changes in the timing and duration of canal releases and changes in crops and cropping patterns.

In the process, the role of canal management may diminish relative to well irrigation.

Venkata Reddy (1988) describes the Gokak canal irrigation system, which irrigates 6,450 ha in northern Karnataka, where shallow wells have been introduced in response to an inadequate canal supply. Opportunities for 'joint use' of resources has encouraged farmers to develop into production of water crops like sugar cane and rice. The main constraints to adoption included brackish groundwater aquifers, hardrock strata, lack of technical advice on tapping aquifers, poor electricity supplies, and irrigation department restrictions. Smaller farmers were especially constrained by lack of capital, and land holdings too small to make economic use of a single well. However, informal agreements between those with and those without wells and special credit arrangements ensures some access to groundwater for most farmers, and some have more than one well to expand irrigated area. Community tubewells are expected to address financial constraints faced by smallholders, and the overflow of wells during canal operation periods. However, Venkata Reddy warns that gains are likely to be undermined if soil fertility is allowed to decline due to more intensive cultivation and lack of integration between canal and dug-well irrigation.

Inequalities in supply between topenders and tailenders are familiar, but they can continue to exist even with conjunctive use developments. This applies to both canal and groundwater irrigation. Conjunctive use promises farmers equity benefits by providing an individual and more flexible supply. But both canal and well irrigation may benefit larger farmers more than smaller farmers who cannot afford to participate. This has been shown for large and small schemes. Wealthier farmers and landowners, who have access to capital and other resources, benefit more from new technology than less advantaged farmers. Smallholders, who may be shareholders or tenants, often lack the capital or credit required to buy a tubewell and are forced to borrow from informal moneylenders at higher rates of interest. Larger farmers can control the supply and inflate prices ('rentseeking'), or manipulate deliveries by persuading gatemen to extend the duration of canal supplies (Vaidyanathan and Janakarajan, 1989). Alternatively, water markets can be a very effective means of water supply (Shah, 1991).

Shah (1991) hypothesises about the role of water markets in overcoming local problems in joint use, and shows a variety of areas of uncertainty destabilising the organisation of water markets, and thus any kind of communal interactions which might begin to crystallise new local

management structures for joint water use. These include charges for electricity, uncertainty about the release of surface water on a general basis, rehabilitiation initiatives which suddenly change water availability, and lack of access to drainage water at effective prices to encourage the environmentally desirable use of these waters.

There is little doubt that field research has demonstrated many equity and production issues in irrigation schemes. Many good recommendations have been made relative to particular schemes, although they often cannot be generalised. These include recommendations on the surface conveyance and drainage system, as well as groundwater. Important concerns have been a decrease in charges made if farmers wish to pump drainage water, or wish to use canals for water pumped from other sources. However, these recommendations often do not get used.

One important reason for this is a failure to recognise who the decision-makers are on particular topics, and the kind of information they can interpret and respond to. Because most researchers are currently working in a 'local water management' paradigm, they usually direct both recommendations and criticisms at water management agencies. Apart from the low likelihood of organisation accepting both criticisms and recommendations, the irrigation department at which comments are directed may not have responsibilities in the areas for which they are criticised, or there may be very, very cumbersome procedures for change which currently remain unseen by researchers anxious for change. Table 2 shows a diagram by Schultz (1989), to demonstrate this issue of different capacities of action by different organisations.

The introduction of well irrigation and drainage requires farmers and managers to adapt management procedures and technical skills to accommodate the new technology. The success of conjunctive use is likely to depend on there being production and income gains for most farmers, guaranteed access to either, or both, resources at the right time, and positive equity benefits. However, should we be looking at water management bodies to coordinate these initiatives? The answer is no. Poor water management is not what is causing the problems reported by research on equity production problems (indeed, local water groups may be functioning fairly well). It is technical innovation that is challenging water management, so we have to look at dimensions of technology policy before we can understand new water management options.

TABLE 2: HIERARCHICAL DECISION STRUCTURE IN WATER MANAGEMENT, NW GERMANY

	Decision Level	Level of water management expertise	Decision Power: engineering	Decision Power: political	Sample projects	Author's client
1	State Ministry	high	medium	high	Rise of Ennepe Dam	Ennepe Water Authority
2	District Administration	medium	low	low	Dhünn Drinking Water Reservoir	Wupper River Authority
3	Regional State Water Authority	high	low high	zero	Wupper Reservoir ↔ Jubach Dam	Wupper River Authority
4	River Authority strong	very high	high --	low	Wupper Reservoir Emscher Flood	Emscher Water Authority
	(public and private members) weak	low	-- low	zero	Retention Reservoirs ↔ Jubach Dam	Water Supply Agency Lüdenscheid

Source: Schultz, 1989.

In studying groundwater options in extending water availability, researchers are tending to see well development as a local water management issue. In fact, well development cannot easily be incorporated into local management, because it is not a locally developed technology.

We know that access to many resources is determined by the role individuals have played in mobilising that technology. Since it is primarily through tax incentives, subsidies and price controls that many farmers have taken up well irrigation on an individual basis, we should not be surprised if we have to turn to these management nethods to look for help with resource management issues, and should not expect water management institutions automatically to play a primary lead in such areas. As Sexton (1991) points out, institutions associated with pump technology were organised to promote technology for agricultural water supply, rather than control it. Also, no collaboration is actually needed to *operate* the technology.

Where conjunctive use has been involved in the reduction of waterlogging, and in the mixing of water quality, and in the provision of public tubewells, we do find public institutions operating to coordinate at least joint use of water resources in the conveyance system. Where institutional studies are weak or non-existent is in the management of individual groundwater supplies. This, of course, is a more general problem in groundwater development.

We should not be surprised at this, since there has been little discussion of communal organisations for groundwater management, since, by and large, donors and state governments have become resistant to further extensive development of public tubewells, and tend to favour private developments. They have also been resistant to development of new bureaucracies for groundwater management. We should not be surprised if 'local water management' cannot coordinate all the new institutional needs associated with technical innovation. We certainly needs to draw heavily on other areas of research if we are to find effective institutions for joint management.

For example, let us take the case of individual well development in irrigation commands where canal water is inadequate to serve a local command. In India, many authors have promoted well development for production and equity reasons and looked at the potential of water markets to help local water management problems. Water bureaucracies have been criticised for not helping more to promote this evolution. However, in India, there are few forums to link the rural development agencies involved with credit, research linked to promoting innovation and adaptation of new technologies, or agricultural support services, with the larger water bureaucracies. These organisations have there own tensions and financial restrictions in helping ares seen to be more privileged. Despite many capable and concerned administrators, they have not been trained to understand each others work, and may not be able to assimilate the complex documentation provided for the discussion of certain problems.

If we keep trying to force rural development changes through public water management agencies, then we will remain with institutions where engineering 'decision power' is strong, social science understanding is weak (despite many motivated engineers), and political powers are low. Trying to make engineers more 'interdisciplinary' may increase understanding, but it will not necessarily make research better or improve decision-making.

Clearly there is a strong need for more studies of how institutions control research and decision-making to influence policy making. Past studies may tell us a lot, but we also have to recognise the challenges of the 1990s. The problem is not only the difficulties of getting political leaders convinced by certain ideas. The problem is also the current poverty and confusion of theory about inducing rural change, that results in national governments and donors with unclear and conflicting objectives. As funds decrease for bureaucracies, as centralised planning becomes weaker, and as state officials change posts rapidly, we need to study the new options for local and state structures that can encompass the findings of existing research paradigms in water management and technical innovation, and also answer the organisational challenges of the 1990s.

5. TECHNOLOGICAL INNOVATION IN THE USE OF WELLS

When we start to look at conjunctive use in terms of production and equity impacts, we are actually dealing with dimensions of rural development and technology policy. This requires a whole gamut of institutions quite different from water management institutions. Groundwater development was studied as an issue of technological innovation in the 1970s (Clay, 1974, 1980,1982), independently of connections with large public surface irrigation schemes.

Such research showed a broader regional concern of 'conjunctive use', where the dissemination of groundwater technology has changed farming systems which were earlier based on heavy rainfall and flood recession. Here dissemination of groundwater technology has fitted well with technology preferences of donor and state organisations, especially where these can be encouraged as private sector developments. Groundwater development has expanded spectacularly in many wetland areas previously cultivated without extensive conveyance and drainage structures, or where wetlands were used for communal grazing activities.

The rapid development of tubewell technology across eastern India and Bangladesh, under waves of different types of pump technology, has been well-discussed. However, groundwater technology is making rapid headway in the river valleys *(fadamas)* and deltas (Woodhouse and Ndiaye, 1991) of West Africa, and for irrigation of the small gardens developed in the seasonally-wet depressions *(dambos)* of East Africa. In Africa, concern at the erosion of traditional uses of wetland is mixed with recognition of the benefit that do accrue to farmers who obtain the pump technology. These areas raise rather different policy challenges, since not only may institutions for surface and groundwater management be diffuse, but land rights may be rather different to water rights.

Tenure complications are, of course, an ongoing problem in irrigation schemes, especially as groundwater gets developed. As Geert Diemer points out (Diemer, 1991), many technical staff are unable to contemplate allocation principles for water as social contracts, and only a few realise that common engineering allocation principles are context-bound and specific. Their training generally anticipates situations where a single institution owns the infrastructure. Such expectations can be equated with current concern to make local water users associations 'stretch' to include all kinds of functions, which they can rarely do. There is a similar logic in O'Mara's arguments (1984) for 'source symmetry' in conjunctive use, with rights similar in surface water and groundwater (and by extension, probably individual and codified).

One important lesson of the early work on tubewell technology was the 'misfit' between the technology introduced and that actually required. It took a great deal of farmers innovation to improve the 'fit', and this involved cooperative ventures from various individuals and agencies in credit, production and equipment development, as well as water management. As we look over the history of technological innovations introduced in irrigation, from canal irrigation to artificial recharge to vertical drainage, we see an ongoing problem of technology that doesn't 'fit' first time, with action required by a variety of institutions to ensure that costs and availability of resources match farmers requirements. The current vogue for formation of water users associations has shown that many technical assistance teams recognise that institutions are required to make their technology useful. However, as the papers in this set by Casey and Jackson show, extensive dialogue with farmers to encourage innovation, and strengthening of a wide range of support services, has been essential. If we return to the documentation on tubewell expansion in Eastern India and Bangladesh, we find a variety of type of cooperatives (production, labour) involved in the adaptation and take-up of new technologies, not only water associations.

Technological change requires adaptation by farmers, operators and managers. Farmers and irrigation staff, familiar with operating canal sluices and gates, may have to adapt to use and maintain engines and pumps which require different skills to canal irrigation. Though an individual supply promises greater reliability, breakdowns and fuel and spare part shortages can interrupt production. Where farmers do not own the tubewell but depend on others for supply, this problem is exacerbated because operators have less incentive to make urgent repairs or carry the necessary stocks of fuel and spare parts. Farmers may face different suppliers for canal and groundwater supply which may cause confusion, with excessive supply in some areas, shortages in others. There may also be a differential reliability across the year causing acute problems in times of high demand. Joint management of two sources is more complex, and in the future the role of microcomputers will probably increase for scheduling and management, at least on larger schemes, and may demand managers be familiar with this technology.

In many places the high cost of groundwater supply, even at reduced heads, may discourage tubewell use. In the Philippines pumping costs may be five to ten times more costly than canal water and farmers will only use groundwater as an insurance against the surface water supply (Weller, 1990). Fluctuations in energy supply, and in electricity tariffs, may make investments in tubewells risky.

At farm level, tubewells have lower capital costs but higher running costs than canal water (Chancellor-Weale, 1989). However, canal schemes are usually publicly owned, capital costs of canal construction (and sometimes running costs) are met by government or donors, and canal water is

therefore subsidised. Tubewells are usually privately owned and farmers face full capital and recurring costs as well as depreciation and replacement. This disparity can make supplementary tubewell irrigation an expensive option compared with other rehabilitation measures. Palanisami and Flinn's (1988) benefit-cost analysis of various options of tank improvement, demonstrated that management improvements were much more cost effective than additional wells (or canal lining). Additional wells yielded a B/C ratio of 1.3 and an IRR of 35 at a discount rate of 12.5%. The equivalent values from improved sluice management were 10 and 2204.

Farmers who own wells, therefore, need consistently higher incomes to justify their investment and stable prices for inputs and outputs (Chancellor-Weale, 1989). The major source of variation in annual costs is the fluctuating demand for groundwater which is largely dependent on the reliability of surface supply. Farmers who purchase groundwater face higher prices in drought years. Irrigators are also effected by the supply and price fluctuations for fuel and spare parts.

Changes in national prices caused by an increase in supply or increase in demand for inputs and outputs may have serious consequences for producers. Chancellor-Weale (1989) cites the case of Bangladesh where changes in both input and product prices have reduced returns to a level where recurrent costs can no longer be met. In the longer term these effects may change the investment decisions of farmers and agencies towards different cropping and irrigation systems.

More generally prices are effected by access and ownership. Wealthier farmers may own their own tubewells, others purchase water from an owner or operator. If water is purchased, farmers face prices set by operators and owners. Where competition between suppliers is limited, farmers may face monopoly prices. In addition the cost of a tubewell unit and its associated structures (pumphouse, canals, gates) is commonly beyond the means of individual farmers and requires collective or cooperative ownership and management. This dualistic system means price incentives may induce farmers to use one or other resource which does not fit with rational regional planning priorities.

6. STUDIES OF INSTITUTIONS FOR PROMOTING CONJUNCTIVE WATER USE

The last three sections suggest a diverse range of circumstances and institutions on which to arrange an analytical framework. However, they all share particular institutional needs:

- identification of decision-makers and information needs;
- formulation of objectives;
- generation of social, economic and political information needs;
- generation and preservation of technical knowledge to inform decisions;
- daily operational management procedures;
- construction/manufacture/installation of new technology;
- definition of access rights;
- resource management procedures;
- means to enforce procedures;
- means for dispute resolution;
- support to adopt new technologies;
- support to adapt new management procedures, new enforcement procedures and new means for dispute resolution;
- forums of discussion and policy evolution.

This list could be developed further, but it stresses the need for a study of the institution problems we must tackle to achieve conjunctive use. One problem is that work in conjunctive use has stayed almost entirely in studies of topics 4-6 above, and as we show later, much of the 'knowledge' generated by research studies and modelling has been very partial. The bulk of existing research in conjunctive use has worked either with *developing technologies* or studying *commodity transactions* within existing institutional arrangements. We have not looked enough at *institutional transactions* to change the rules, whether directed by organisations or induced by economic forces (Ashford and Biggs, 1991; Bromley, 1989). The limited research available on institutional issues in joint water use nevertheless shows up the diversity of issues to be considered, and the breadth of institutions involved.

Vaidyanathan and Janakarajan (1989) compare the effects of conjunctive use developments on operation and maintenance in two tank systems in Tamil Nadu. The Palar Anicut System (PAS) in N Arcot district serves 33,000 ha through 317 tanks. It is government-managed down to tank level, and locally managed thereafter. The Parambikulam Aliyar Project (PAP),

in Coimbatore and Periyar districts, serves 73,000 ha, over a generally drier area (therefore comparatively higher returns to irrigation), and is government managed at all levels. Conjunctive use has contributed to increases in irrigated area, cropping intensities and (hence) yields in both areas. Although levels of local and government involvement in management are different, they note that the physical characteristics of the system were found to be more significant than institutional forms on productivity. In PAP, the expansion in groundwater supply resulted in large increase in irrigated area, and canal water had to be spread more thinly. The frequency of water releases into the tank system has been decreased to once every 18 months, and continuous supply has been replaced with an alternating week-on, week-off supply. Overall groundwater irrigation was encouraged by relaxing restrictions on well sinking. However, attention to distribution of surface water and maintenance of canals has declined with the development of groundwater.

Three examples of national conjunctive use policies are compared by O'Mara (1988). California has adopted a heterogeneous path which includes a system of riparian rights, water user associations (WUA), water agencies, water districts and consultants. The state offers a guaranteed supply and controls are through pumping taxes and adjudication. Water management includes artificial recharge and barriers to saline intrusion.

In Pakistan a system has evolved through SCARP I and II comprising quasi-legal allocation principles of historical water rights and distributive justice. These are considered to fare better than institutional solutions (fungible legal rights, efficiency taxes, subsidies, central and local control) which have had limited success in Pakistan, or efficiency guidelines. Success will depend on improvements in monitoring, administration, farmer participation, pricing and fee collection procedures.

In the North China Plain, surface water irrigation was relatively well developed until superseded in importance by groundwater in the 1960s and 1970s. Organisation is hierarchal under the commune-brigade-family system. Conjunctive use has improved efficiencies in the lower reaches, where surface water is used to irrigate land close to the canals and groundwater to irrigate land which is further away. However, there are problems of falling water tables and land subsidence, deterioration of well capacity, and inefficient use of water and energy. Water is spread too thinly and the supply is often inadequate. Institutional problems include divisiveness, poor legal provision to settle disputes, emphasis on construction over operation and maintenance, the lack of adequately trained and adequately motivated personnel, inadequate secondary and tertiary canal development and coordination, unauthorised offtakes, and topender/tailender inequity. The Chinese response relies more on quasi-legal allocations than institutional reforms although leadership is committed to these where they will bring significant gains.

O'Mara concludes that most legal-allocative and efficiency criteria are satisfied in all three cases except for source symmetry (the equal treatment of surface and groundwater) in Pakistan and California. However none are considered to have satisfactory institutions (defined as 'efficient and workable') to implement effective controls over resource use. California favours local controls and a pumping tax, China prefers local administration and the ease of administering taxes or quotas through the commune system, though pumping taxes (or quotas) would seem to be a likely ultimate choice. Pakistan has rejected centralised control and is facing a dilemma between a tax/subsidy policy or a legal rights scheme. O'Mara considers neither is feasible until some form of water user association (WUA) is in place.

O'Mara's choice of the term 'water user association' is unfortunate, because the kind of local institutions required in situations of joint use are very different from the 'water users associations' that are really local groups for the distributions of water. Under joint use, individuals have • no real incentives to collaborate for operational reasons. They may, however, need to cooperate for resource management purposes (to stop others using their water), or as a more general body to make representations to government to protect resources, or to deal with taxation and marketing needs delegated to them by governments. In short, they may need to become a broad-based farmers' association, or that unfashionable thing - a cooperative. In their study of irrigation in the Senegal delta, Woodhouse and Ndiaye (1991) show surface and groundwater being coordinated within village institutions whose structure was determined by local needs over a wide range of agriculture-related activities in marketing, credit and supply of inputs. Village institutions survived also because of indigenous land tenure arrangements. Ironically the growing 'privatisation' of land being encouraged by state irrigation policies may actually be threatening the strength of many indigenous institutions.

Lemoine and Gosch (1985) speculated that in California, the magnitude of benefits of reorganisation and collective action would be insufficient to induce farmers to pay the necessary transaction costs. Clearly, if we want

strong local groups that can make operational *and* resource management decisions, we are going to have to encourage their development. The research paradigm that supports the development of 'water users associations' will not be adequate, and looking purely at options in terms of FMIS will not be helpful. We must consider a wider range of functions for a water group, and the nature of its relationships with many dimensions of the agricultural sector, and the state. We need to use the large body of research on the influence of technology policy and findings on links between the wider institutional framework and innovation, technology adoption, and technology adaptation. It is not only local traditions in water management that help in innovation and adoption of new technologies. It is also the existence of other productive reasons to collaborate, and economic factors like the operational costs of the technology, security in return to investment in that technology, and profitability of goods produced, many other reasons.

We have similar dilemmas when we look at options in regional level development of conjunctive water use. Surface water and groundwater are often governed by separate authorities. Rivalries and poor coordination may result. Carruthers and Stoner (1981) cite the extreme example of Bolivia where two authorities put up schemes, one surface water and one groundwater, to irrigate the same piece of land. Further, surface water may be government owned and managed while wells may be privately owned. Hence regional authorities may have better control over surface water management and pricing than over groundwater, and policy may be ineffective. There are special implications for conjunctive use which demands the integration of surface water and groundwater management systems under one planning authority or user group.

In Pakistan the integration of regional planning and irrigation activities has been relatively successful. This has been attributed to WAPDA's institutional strength, an established tradition of hierarchal management, and the good technical and organisational skills of managers and engineers. However, the model is elsewhere criticised for its high requirements in manpower, technology and institutional cohesion. The system relies heavily on good data collection, the use of computers for data handling, and planning models, and a complex management system comprising department officials at every level. The system would be of more limited use where capital and human resources are scarce and institutions less developed.

The introduction of groundwater irrigation may disrupt established access entitlements to land, water an other resources, causing conflict and threatening its sustainability. Joint use may require the redefinition of the responsibilities and jurisdiction of social institutions to ensure access to either or both surface water and groundwater for participating farmers. Legislation relies on a relatively strong centralised authority, usually the state, and institutional cohesion. Where these institutions are weaker and informal rural politics are more significant, government policy is less effective. Where the state is very large and government has limited resources (e.g. China), there may be a tradition of village autonomy in resource management.

Riparian rights may entitle farmers to their full irrigation requirements from a river and restrictions on offtakes, or the introduction of charges, may meet with resistance. In canal schemes the frequency and duration of canal turns are usually determined according to the size of individual holdings or blicks, and much less commonly by volumetric consumption. A private tubewell owner, on the other hand, may be entitled to all he can pump in spite of the fact that this reduces the stock of the resource, and access to it for other users. Further, a well-owner who can pump unlimited groundwater is less likely to use canal supplies and the canal system may fall into disrepair. Complex legal questions also arise over river basins and aquifer units that are wider than regional and national boundaries (Barberis, 1986).

If we look at options for conjunctive use at the regional level, we will also need to look beyond simple components of institutional reform, and look for incentives and disincentives to impinge on production and resource use decisions by farmers. Systematising land and water rights to fit a centrally decided set of legal controls is not possible in many countries, nor can it be enforced (as previous examples show, these could actually be counterproductive to local cooperation). As the state bureaucracies become weaker as a result of financial constraints and changing government and donor policies, we face real challenges in understanding how both legal, economic and social incentive can emerge for conjunctive use of resources.

Centralised planning and the scope of public intervention are also changing. We must consider not only how this affects bureaucratic collaboration for policy formulation at the centre. We must also be concerned at how this may atomise the interaction of local agencies implementing these policies (in rural development, agricultural support, and water management), especially if we really want to achieve conjunctive (optimal) water use as well as joint use.

7. THE HYDROLOGY OF CONJUNCTIVE WATER USE

This section summarises some hydrological features and issues in the use of conjunctive water in its original concept - to maximise available water in technical water resources planning. Here conjunctive water use is a term used to describe the use of surface and groundwater in such a way as to increase the proportions used of both resources, to make maximum use of available water resources, and minimise any losses from either resource. The term has its roots in the concern over growing inadequacies of water supplies in Western countries in the 1960s, and it is important to note that initial ideas grew up in countries with temperate and fairly well-defined seasonal climates, and also relatively small catchments. In many of the Western countries at the time, the institutional configuration for water extraction also made this model administratively straightforward to consider. It liberated more water within a technical system under unified management. Today, with concern about finite reserves, we are looking at much more complex alterations between users and between managers.

Typically, groundwater is pumped to draw down water tables so that more surface water infiltrates. More water infiltrates from high flows and floods, which might otherwise have been lost to sea. This recharge can be natural or encouraged through artificial recharge. Groundwater extraction would predominate before, and across part of the season associated high river flows, but care is needed at other times, both in surface and groundwater abstraction, to ensure that minimum baseflow in rivers is preserved. Groundwater recharge consists of directly infiltrating rainwater and seepage from rivers, canals and reservoirs which are 'hydraulically connected' with underlying aquifers (i.e. there is little impermeable material between the riverbed and the aquifer). When groundwater is high, it may contribute to the baseflow of the same streams and rivers.

Conjunctive water use in irrigation often extends to mobilising good qualities of water as well as good quantities of water, as well as gaining benefits in drawing down water tables which otherwise acerbate waterlogging and salinisation. Table 1 showed the typical range of operational circumstances for conjunctive use in irrigation, and the types of technology which will have to be adopted and adapted in each area. On an irrigation schemes the natural elements of recharge and drainage combine with seepage from irrigation practices. This includes seepage from the irrigated area, and from the base of associated distribution and drainage canals, and reservoirs. This provides 'artificial recharge' to groundwater in the dry season and produces a localised rise in the groundwater table. Under conjunctive use, water 'lost' from canals and irrigated fields can be re-used by pumping it from the aquifer and combining it with surface water for high overall efficiencies (Rushton in Gorelick, 1986). Again, pumping can draw down water levels artificially, so that surplus surface and rainfall are encouraged to replenish the aquifer. Alternatively, low quality canal water can be 'recycled' by pumping purer water from aquifers adjacent to canals (Huang quoted in O'Mara, 1988).

The re-use of canal seepage by pumping a near surface aquifer offers the twin advantage of lowering the water table and reducing groundwater pumping costs. This reduces the need for improved hydraulic efficiencies by canal lining, or piped irrigation. Tubewells provide a supplementary source of irrigation water and the means for irrigation authorities to control waterlogging and salinity.

Conjunctive water use is not always seen as an automatic priority when we look at other objectives. For example, it might be argued that a near surface water table is not good practice for irrigation if environmental problems are to be avoided (Rydzewski, pers comm). Energy might be better spent in improving horizontal drainage systems and reducing the seepage from canals by lining. Further, controlling withdrawals requires good monitoring and institutional cohesion which is often lacking in less developed countries.

Despite a simple theory, the practical difficulties of developing optimal conjunctive use are significant. We have already discussed some of the institutional complexities. Hydrological complexities include difficulties in quantifying the volume and timing of available flows of surface and groundwater. In many areas of the world, even under irrigation schemes, prevailing rock types hold limited water, and the degree of 'hydraulic connection' between surface supplies and recharge from surface water is weak and unpredictable. In Appendix 1, we summarise some of the typical elements studies in hydrological models for conjunctive water use, and the difficulties admitted by experts in the field. Estimation of seepage, and derivation and use of key parameters of groundwater movement have been particular problems. Sadly too, much groundwater theory has developed to answer questions on regional water availability, and on responses to heavy-duty or large capacity tubewells of the kind found in large-scale public water supply systems in industrialised countries. We still have very limited theory to show how large-diameter dug wells behave, or predict how water levels in wells change over time.

Clearly, the hydrological concept of conjunctive use is applicable at both a small and large-scale, including developments at local and regional level. As water resource become more heavily utilised, administrators are increasingly looking at ways to maximise resources. However, when we move to more complex river basins in more extreme climatic circumstances, especially if they are intensively farmed, practical hydrology becomes more difficult (apart from the questions of institutional collaboration). In areas where the time of rise and duration of high river flows is unpredictable, it is not easy to draw down water tables in advance. What happens if water levels fall and the surface flow does not arrive? Who will pay the increased pumping costs of such a policy or, compensate farmers without water? Perhaps flood flows should be stored and recharge encouraged, so flows are not lost to the sea. However, where can the ponds for artificial recharge on a large scale be sited? Who will fund the high costs of artificial recharge, especially in areas where the links to actual recharge are weak or poorly understood? In areas with hard metamorphic rock, the depth of weathered rock, and thus of water storage potential is limited. Storage in such geology may be replenished by one rainstorm. How can it be systematically draw down so that more surface flow infiltrates rather than runs off?

These are some of the technical issues which have created complex problems for the promotion of conjunctive use at regional level, especially where the objective of optimal use of available water is not the key priority. A fuller technical discussion is given in Appendix 1.

8. MATHEMATICAL MODELLING IN CONJUNCTIVE USE

Models have a chequered reputation in the field of conjunctive use, with both supporters and detractors. As noted, we find very few published studies evaluating the utility of models constructed to study conjunctive water use. However, we have a very interesting set of views from some people involved in the construction of models. Some model builder do criticise the art, noting its tendency to be divorced from reality, and to prefer complex techniques to simple one (Biggs, 1984; Schultz, 1989). Schultz (1989) discusses the 'ivory tower' people who assume that planners preferences can, and should, be directly dictated in terms of parameter values for a model, or who expect decision-makers to be able to work with mathematical information cited directly from the model. He also points out that modellers often naively assume that the decision-maker is a person, able to accept a single optimal solution. However, decision-makers are often complex systems of people, and can rarely accept a single optimum solution. Thus a dialogue is never created, and decision-makers remain as 'ghosts'. In reverse, model-builders are disappointed to find that no-one uses the model.

Wunderlich (1989) reminds us that there is no unbiased approach to an uncertain future, and thus assumptions much be made clear to decision-makers, or every attempt must be made to study their biases. This of course, also requires discussion. Stephenson (1989) also reminds us of the actual bias within modelling. Established donors, planners and engineers all have preferences in techniques. It is very important in model building to have *end-result* contracts rather than *method-related* contracts.

We find many environmental models aimed at portraying the hydrologic interactions between surface and groundwater. These combine a water management model and an optimising decision making model. The former simulates surface and groundwater flows and offers the user a range of water management options. The optimisation model compares various combinations of surface and groundwater, and selects an optimum combination based on hydrologic, economic or allocation criteria, for example minimum conveyancing, least cost, water quality or resource conservation. A more rigorous definition and a review of groundwater models is given by Gorelick in O'Mara (1988). Some are summarised Appendix 2.

Models simplify reality dramatically. Simpler groundwater models commonly assume aquifer conditions to be isotropic, homogeneous, and prescribe single values for transmissivity, storage and specific yield. While an alluvial aquifer, or a simple sedimentary aquifer can be modelled relatively easily, it is very difficult to study flows in hardrock aquifers. Field conditions are of course highly variable in space and time. As discussed in Appendix 1 the unpredictability of seepage and drainage causes special problems in conjunctive water use studies in irrigation. In sensitivity analysis, Rogers and Smith (1970) found return flows from drainage an important source of variation in potential outcome in their regional planning model, and one of the most difficult elements to predict.

In addition there are agricultural planning models which simulate the response to changes in policy variables. Many of these models have a specific focus on rural development and poverty alleviation. In their broadest form, such models portray the role (and the impact) of changing irrigation technology in the agricultural sector. They attempt to predict changes in the

economic behaviour of farmers to changes in the availability, and relative supply of surface and groundwater and the impact on farm outputs and incomes. This might include changes from one source to another, changes in management of supply, or changes in cropping patterns and intensities.

Although there are a range of agricultural and rural development models that could be used to look at the rural development effects of conjunctive water use (see Biggs 1982), few have actually been used. Stephenson (1989) also provides a study of the inappropriateness of many general economic assumptions in cost-benefit analysis when modelling economic benefits in developing countries.

Most existing models looking at rural development aspects of conjunctive use are large-scale, aggregated over regions. We have many fewer models looking at the schemes level, and we could not find any models looking at the village level. Although such models could have been developed to optimise equity issues, most were actually concerned either with maximising food production, or with looking at efficient cost aspects of water development. Both the levels of aggregation and types of variable uses all tend to make such models rather useless for predicting actual equity effects, except in crude terms of topenders and tailenders. Most of these models combine a fairly crude hydrological model to portray water availability, with a stylised crop production package for a 'representative' farmer. Sometimes they may also include production functions for linking improved yield with better water control. As Biggs (1982) points out, although such models could include many more variables that typify *actual* rural conditions, they rarely do. Elements that could be included were availability of assets, transaction costs, actual labour availability, the variability of crop and employment options for small farmers, sharecroppers and labourers. We did not find any models constructed to examine the differentiation effects of conjunctive water use practices, or the local constraints to adaptation of new technological practices.

Put simply, regional planning models that have been constructed to date have been set up purely to answer macro-questions about the scale and costs of hydrological developments to achieve yield gains. Despite their apparent algebraic complexity, both the hydrological and economic relationships inferred are often very crude, and the data input for parameters very weak. They may have their uses for certain kinds of investment decisions, but great care needs to be taken in good sensitivity analyses to ensure that results portrayed are useful.

Where models are set up with clear and relevant objectives, and use sensible data, they may be valuable to planners, managers and scheme designers. However, modelling is very expensive, and takes up skilled manpower. Coordinators of research should look carefully to see if models can give a good picture of objectives before a great deal of money may be wasted in modelling.

Users should be aware of the nature and significance of simplifying hydrologic and economic assumptions which limit their descriptive capacity. Hydro-geological conditions are very rarely homogeneous but vary widely in space and time. In difficult hardrock environments aquifer hydraulic behaviour may be unpredictable. Single values of parameters like transmissivity, permeability, are unlikely to be very representative and extrapolating from field to regional scale compounds the error.

Simplifying economic assumptions that farmers are independent, price responsive, income maximising and risk averse, and have access to both surface and groundwater supplies, and to each if the other fails, are often false. The assumption of physical interdependence between water resources makes the assumption of independence between farms invalid - there are no free optimising economic agents (O'Mara 1988). In less developed countries where farming is difficult and risky, farmers may forfeit maximum income for reliable income over a stretch of drought years. They are subject to constraints such as whether the supply is operational, and whether they can access that supply. As for hydrological variables, extrapolating the behaviour response of one farm to regional level obscures the differences in endowments and incentives between farmers at field level.

Who will use the model? A policy evaluation model may be used by an agency, a government planning authority, and water and river basin authorities. Conjunctive use scheduling models will be aimed at scheme managers. There is a danger that they will be taken at face value when simplifying assumptions are not explained or understood. Is the model is to be used with caution by well-trained staff able to judge when the model's recommendations should be overridden? Or is the model to be used by semi-skilled staff who use the model uncritically when training and staff development will be required? We know of examples where conjunctive use models were used to identify 'surplus' groundwater and surface water across a river basin. Although the technical studies ran over many months, it was set up purely on hydrological theory and data, with no concern for the users of the information, or practical local development procedures. The results

were disseminated to administrators and politicians in a one-day seminar, and from that they were supposed to adapt complex decisions on whether, and how, to change existing procedures for deciding groundwater and surface water developments. Where farmers are more directly involved in management, models may be of even less usefulness. They rather need to understand the nature of the resource and simple budgeting for it's management.

Will the results of a model be available on time? Many models take months to come to fruition, by which time data may no longer be correct, and the entire institutional context for decision-making may have changed. Good modelling depends on good monitoring and information. This depends on a developed system of data collection and analysis which is lacking in many less developed countries. Moreover, models must be calibrated by groundtruthing in the field, and improved over time as new information becomes available.

Some argue that modelling is too rarely applied in the field, especially in less developed countries, and should contribute directly to improved irrigation management (Khepar, 1990). However, of over 700 models described in the UN's Water Resources Journal, only 5% have been used in the field (Biswas, 1990). There is certainly a danger that models will divert resources away from other priorities and preoccupy the research staff of water departments. Nevertheless, simple 'user friendly' models may be useful for conceptualising and studying simple objective in conjunctive use.

However, if we return to our current planning dilemma of conflicting objectives in joint use of water resources, it seems that models constructed to date cannot help us very much. If we return to our list, we have seen models linked to questions of the costs and returns to technical investments, and those looking at rehabilitation. However, we have not seen any that link up questions of rural development and equity with changing water technologies and optimal use of water resources. It is very rare indeed for modellers to interpret their results in terms of management needs, although Lemoine and Gotsch (1985) did try to try some general conclusions (see Appendix 2).

9. CONCLUSIONS: DEVELOPING THE INSTITUTIONAL FRAMEWORK

One way forward to examine the critical issues of forums for better debate, and to cut across conflicting objectives, is to look for complementarity and not to get overwhelmed by complexity and fragmentation. In fact, all these different objectives bring us back to essential questions about *institutions*. Failure to look at existing and potential institutions, and above all how they can link and inform each other, has been an essential limitation in the work on conjunctive water use to date. By clarifying objectives, even where multiple, we can then develop the theoretical model to identify the areas of research needed, the tools to use and the relevance of existing research. With understanding of the outcomes to be achieved, we can then make careful analysis of institutional needs and decision-making processes.

We feel that some of the limitations in research and implementation for conjunctive use have been:

- unclear or partial definition of objectives (e.g. to consider rehabilitation without looking for more optimal use of water);
- failure to examine the full range of institutional issues;
- failure to clarify decision-making processes and needs;
- lack of definition of research methods and information sources to examine objectives;
- poor use of available bodies of research;
- poor evaluation of research methods, so that approaches continue (especially in modelling) which have limited contribution to evolution in water management;
- recommendations from research are being directed to wrong institutions;
- a tendency to expect water management institutions to encompass all technology innovation issues, whereas what is often needed is more liaison between water management institutions, rural development

institutions and other support services to promote technology adoption and adaptation.

Without a clear statement of objectives in promoting changes in water management, there can be little real evaluation of outcomes, and the decision-making needs to ensure relevant institutions evolve.

One of the interesting features about the papers by Sawant et al in this set, is a sense of looking to see how the debate can go forward in ways that are politically realistic. The paper demonstrates the point of working with the institutional transactions preferred by those involved, which in their case is the avoidance of *directed* organisational change. From the literature it is clear that donor activity has been important in requesting and supporting forums for discussion, and Sawant et al's paper shows that this has not changed.

When we are looking at the dissemination of new technological initiatives and management needs it is important, too, that we go back to understanding institutions in their fullest sense. One of the difficulties resulting from the focus on local water management over the last 15 years is that we increasingly expect water organisations to handle all aspects on innovation, and undertake research with this focus. We have also become restricted in the type of organisational structures we seek to impose. In fact, in innovation we need to call on a wide range of research and support services that go well beyond water institutions, be they state, communal or individual. Often in looking for changes in the structures of water institutions for better performance, we have lost sight of the issues in *linking* institutions and encouraging dialogue.

In the 1960s the concept of conjunctive use was based in ideas of mobilising more water within the supply sector (although as Schultz [1989] shows, even here there are complex questions of institutional interaction). However, in the 1990s we are looking at needs to link up complex social and economic interests, both among *suppliers* and *users*.

If we are to disseminate new technology, and encourage innovation in water use and water management, we must be informed about the restrictions and potentials of existing management institutions and support services to encourage new developments. If we wish to promote equity and ensure profitable and sustainable production, again we become involved with institutions. If we put institutional reform back at the centre of debate on conjunctive use, then we can use all available bodies of research information, and ensure that we get more integrated reform not only of local water management institutions, but of scheme-level management and institutional developments in agricultural support services and research. In the accompanying paper by Sawant et al, it is interesting that we do not even know the context of the interest in 'conjunctive use', but we do see some interesting development of certain key institutions beginning to acknowledge the issues that are restricting the development of more optimal water use.

This is not just a problem of 'blinkered' research - we must also recognise the refusal of many water institutions to play a role in discussions. Indeed 'institutional reform' has become so linked with the politics of many irrigation bureaucracies, or disagreements between donor recommendations and national needs on water institutions, that we have not only lost sight of the original broad meaning of 'institutions', but many have also lost the will to look at options to reform these institutions. Results of this confusion have included a focus on technological intervention to avoid difficulties in bureaucratic reform and improved information exchange, and the limitation of much social research to tertiary level issues in water management and water markets.

Until existing institutions become prepared to discuss the changes they will countenance in water management and various legal and fiscal arrangements, or to admit the uncertainties they face, social scientists are unable to study the potential impacts of new water provision. Social science investigations will remain confined to tertiary level studies relating to equity issues. For social scientists, improved debate of their work will not be encouraged by simple criticism of bureaucratic behaviour. It will come from looking to strengthen linkages between institutions, and greater debate on the 'art of the possible'.

These are fine words, but of course we need to acknowledge how difficult this is. Furthermore, the extent of state withdrawal from water management which is taking place in many countries makes the ideas of forums of debate and institutional strengthening even more difficult. The growing strength of an environmental focus, in which irrigation has a chequered (and often negative) image, also creates new pressures. The loss of status of many technical agencies now they have fulfilled their supply duties (as shown in Sexton, 1991), adds to uncertainties of effective debate. One important step will be to detach ourselves from dominant research themes, and move on to

new activities where we can draw on useful findings from these themes but not be restricted by them.

In Section 6 we tried to show the matrix of the institutional issues that need to be addressed both to achieve 'joint use' as well as the optimal conjunctive water use. Participation of existing institutions in this framework would enable a far more effective socio-economic critique both of necessary institutional changes as well as likely development and equity impacts at the local level. It is likely to be particularly useful if we are looking to make joint water use more optimal in resource availability terms.

It is not for us to say for which objectives should be given priority in programmes affecting water management. These programmes will nearly always be pragmatic, however much we wish otherwise. However, while seeking to promote optimal water use as the key priority, we can nevertheless also improve debate on optimal water use in the context of other objectives. A central requirement in the achievement of objectives is always identification of institutions that will be involved in decision-making, and be involved in their implementation. A technological approach that tries to avoid management reform will simple end up repeating many mistakes, and curtailing resource management options in the future.

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APPENDIX 1:
THE HYDROLOGY OF CONJUNCTIVE WATER USE

The principles of hydrological interaction between surface and groundwater is widely understood. However, it is often difficult to describe the availability of water locally, both in strict environmental terms and in terms of the probabilities of availability of surface and groundwater. Water availability models usually try to deal with both the hydrological parameters that control the movement and quantum of water available, and the actual likely arrival of resources. Hydrologists tend to be interested in the former, whereas farmers are probably more interested in the latter.

Sources of sub-surface flow include drainage through the soil and influent flow from rivers, canals and reservoirs. The rate of recharge depends on the degree of saturation, the permeability (or hydraulic conductivity) of the subsoil between the ground surface and the water table (or phreatic surface), and on the 'leakiness' of the aquifer, i.e. the rate at which percolating water transmits vertically and laterally within the aquifer.

For saturated conditions the rate of percolation through the subsoil is assumed to be the product of its permeability (or hydraulic conductivity) and hydraulic head. For unsaturated conditions permeability also varies with water content. Most irrigation seepage calculations assume fully saturated conditions. Rushton suggests a value for saturated hydraulic conductivity of 5 m/d for sands and 0.001 m/d for clays.

For relatively uniform hydrogeological conditions, for example the alluvial river basins of S.Asia and China, seepage is predominantly vertical (with perhaps 10% moving laterally) and shallow aquifer groundwater is recharged directly each season. Rushton computes a seepage rate of 1.95 mm/d for SCARP. However, for heavy black cotton soils, clay pans and other less permeable strata, seepage rates may be reduced to 0.5 mm/d (ibid). Recharge to deeper aquifers and in hardrock areas may be indirect, infiltrating in one area and transferring underground.

Seepage from fields is generally more significant than that from the canal network because of their greater relative area and because canals may be lined. Seepage losses can be maintained around 2 mm/d by puddling but actual seepage rates may be nearer 20 mm due to evapotranspiration and percolation into unsaturated bunds and adjacent fields (ibid).

Seepage from canals is usually assumed proportional to wetted perimeter and expressed as a seepage per unit length of canal. However, water generally flows vertically to an underlying or permeable layer and horizontally to a distant fixed head boundary, ie another canal or a drain. Hence the rate of seepage depends on the distance to the boundary, the change in head and the permeability of the subsoil and the canal lining. Rao (1990) recorded canal seepage of 0.2-2.1 m^3 per day per meter of canal (m^3/d/m) for cement lined canals spaced 400 m apart in Mahi Right Bank Canal command (MRBC), Gujarat. This compared with 1.1 m^3/d/m using the wetted perimeter relationship.

Aquifer 'leakiness' is estimated as the product of the hydraulic head and the transmissivity (T), so for a uniform alluvial aquifer, a head of 2 m and a transmissivity of 2000 m^2/d, the lateral flow is 4 m^3/d. For a hardrock aquifer where the head remains constant (say 10 m) and T varies from 50 to 70 m^2/d over 1 km, the change in lateral flow is 0.2 m^3/d over an area or 1000 m^2, equivalent to a vertical flow of 0.2 mm/d (Rushton).

Canal lining can reduce canal seepage by up to 25% (Rushton, Palanasami & Flinn, 1988) and is an important component of rehabilitation schemes. The lining material is usually cement (in slabs or interlocking sections), a bituminous membrane or occasionally buried plastic sheeting. In practice linings deteriorate and develop cracks and holes which may have a disproportionate effect on permeability. Rushton estimates that cracks and holes equivalent to 0.4% of wetted perimeter in a 10 cm thick lining may cause.losses equal to 75% of those for unlined canals. This suggests canal lining is only successful when the lining is in virtually perfect condition. Further, canal lining may be inappropriate in low and medium rainfall regions where seepage losses from fields and canals may be considered a gain to groundwater, reducing pumping costs and encouraging conjunctive use (Dhawan, 1988).

Seepage rates vary with the change in position of the water table through the irrigation period. Hence Rao (1990) advocates an alternating management system under which aquifers are first pumped to lower the water table to its design value, then the canals are operated to raise it again before the next cycle of pumping, thereby maintaining an acceptable equilibrium recharge rate.

A sustainable conjunctive use system relies on maintaining the groundwater balance over time. In Pakistan and China, widespread tubewell use has been used to lower the water table to reduce salinisation and maximise leaching. It is estimated that 2 m is the minimum depth to water table in uniform deltaic soils to provide adequate leaching and prevent salts entering the rooting zone (Ren Hongzun, 1990).

However, uncontrolled tubewell use may cause problems. High well densities and discharges may cause mining, an increase over time in the mean depth to the water table greater than that which can be sustained by conjunctive management. Consequently shallow tubewells (which lack the capacity to pump from greater depth), wells in higher areas, and those not supplied with canal water, may dry up. Well densities of one well or more per ha are not uncommon in areas of India and Bangladesh (for example, Vaidyanathan and Janakarajan, 1990). In addition, the depth to water table will vary across a well field. The phreatic surface is not flat but is conditioned by the radius of influence (RI) and cone of depression of pumping wells. This depth variation and interference between the RIs of adjacent wells may cause drawdown in excess of the design depth to water table in localised areas. Groundwater pumping near coastal areas may encourage saline intrusion as saline groundwater transfers to occupy that part of the aquifer vacated by pumping. Excessive abstractions may cause deeper aquifers to settle, causing a permanent reduction in the groundwater resource and land subsidence at the surface.

Well spacing may be governed by regulations which specify the minimum distance from canals and maximum permissible discharges. For example, in Tamil Nadu the minimum distance was 400 m from a main canal and 200 m from a distributary before being reduced to 200 m and 100 m respectively to encourage conjunctive use (Vaidyanathan and Janakarajan, 1990). Wells spaced too close to canals or of large capacity may induce seepage. A detailed hydrogeological study of the area is necessary to draw up guidelines for well siting and capacities.

Good management and control is specially important if these externalities are to be recognised and checked in good time. Hydrogeological surveys and long-term monitoring of groundwater levels is necessary to chart the behaviour of groundwater in space and over time, and spacing and discharge controls are necessary to keep well pumping within the designed capacity. However these resources are lacking in many less developed countries.

APPENDIX 2:
CONJUNCTIVE WATER USE MODELS - SOME EXAMPLES

(a) Water Management Models

Water management models allow the user to alter physical variables in one part of the system to simulate the response in another. For example, a reduction in the frequency or duration of canal turns will reduce recharge and be reflected in a change in the level of the water table. The rate of response will be determined by physical parameters for subsoil conditions (e.g. permeability) either contained in the model (endogenous), or variable by the user (exogenous).

Conjunctive use models may include surface and groundwater components. At the surface a water balance divides irrigation water into infiltration, evapotranspiration and evaporation. River and canal flows may be treated deterministically, i.e. reliable in time or, less commonly, probabilistically. Recharge to groundwater may be estimated from fluctuations in groundwater level or related to percolation rates in the unsaturated zone.

Groundwater flows are assumed to conform to equations for Darcian flow in a porous media (e.g. Laplace), and for diffusion and advection (e.g. Bear, Verrujt). The area of interest is divided into discrete subareas of regular (finite difference) or irregular (finite element) shape, and the values of decision variables specified at the boundary by the user. Parameters are estimated for aquifer characteristics (hydraulic conductivity, transmissivity, and co-efficient for storage, diffusion and advection co-efficient). Drawdown from pumping stresses are usually modeled on type curves (Theis/Theim). Physical decision variables include heads, and rates of pumping and recharge rates.

Models simplify reality dramatically. Simpler groundwater models commonly assume aquifer conditions to be isotropic, homogeneous, and prescribe single values for transmissivity, storage and specific yield. Field conditions are of course highly variable in space and time. They therefore must be used with caution and the results of the simulation used critically. We look here at some of the models used for decision-making in the irrigation sector (there is a much larger body of work on water resources management which we did not have time to critique).

Regional water management models may be used to simulate regional flows between surface and groundwater resources and estimate potential storages and releases. For example Hossein et al (in AIT, 1990) developed a model to simulate the integrated use of surface and groundwater in Kumubu Project, Kelantan, Malaysia. The existing water supply was found to meet only 61% of demand in a critical year or month. It was claimed that conjunctive use could solve the problem of water shortages for irrigation, domestic and industrial use in dry periods. A model is used to optimise the combined operation of available and proposed surface and groundwater sources at minimum cost in a partially gauged catchment over a 26 year planning horizon. The following parameters are required to input the conjunctive use model:

(1) Surface water balance; (2) Surface Water Resource (based on low flow analysis); (3) Water Rights (assumes users have equal rights within categories but gives priority to domestic and industrial over irrigation); (4) Surface Storage Facilities; (5) Existing Weir Supply; (6) Water Re-use (of irrigation water returning to channels); (7) Subsurface Hydrology (extent, capacity, safe yield and recharge); (8) Cropping pattern (hence crop water requirements over season); (9) Salinity (a minimum residual flow is required to avoid saline intrusion); and (10) Monthly Total Water Demand (for each category of use).

The optimum design recommends an increase in canal supply from 49 to 80 $M.m^3$/month (million cubic metres per month), an increase in groundwater pumping capacity from 1 to 14.5 $M.m^3$/month and a surface reservoir of capacity 30 $M.m^3$. These very considerable increases are possible because groundwater pumping was very low before the project and the provision of a surface reservoir is possible. More usually groundwater is not so under-utilised, and surface flows may be inadequate to sustain a new reservoir or raising the level of an existing dam crest.

Paudyal and Das Gupta (1987) developed a model to simulate the operation of a groundwater reservoir with surface water for Tinao river basin in Southern Nepal. The model outputs optimum combinations for surface and groundwater each month for changes in volumetric recharge. The groundwater reservoir is treated as a renewable resource with a limited reserve. Preference is given to surface water which is assumed to be cheaper than groundwater. A water balance assumes natural recharge to be equal to rainfall in excess of losses due to runoff, evaporation and evapotranspiration. To this is added artificial recharge from canals and irrigation channels, and seepage induced from canals by adjacent tubewells. Monthly parameters include crop water requirements, minimum downstream demand, a weight for relative shortages and factors for streamflow availability, deep percolation and return flow. The model confirms the expected result that in wet periods the proportion of surface water increases relative to groundwater, and decreases for dry periods. The model can be extended to include stochastic streamflows, surface reservoirs and water quality considerations.

Morel-Seytoux and Restrepo (in Gorelick, 1986) developed SAMSON (Stream-Aquifer Model for Management by Simulation and Optimisation) which consists of a physical model and an allocation or decision making model. The physical model simulates daily surface water flows and weekly groundwater flows for any time horizon. The river water distribution system is at four levels, river headgate, supply area headgate, farmgate, and plant level. Supply is determined by crop water requirements, physical constraints (e.g. canal carrying capacity), allocation constraints (quantity or priority of water rights), and losses due to seepage, runoff, evaporation and evapotranspiration. The allocation model is based on operational rules, which may be legal, agronomic, or governed by the magnitude of flows from a river or aquifer. Decision variables include diversions from streams or reservoirs and pumping from wells. It was verified at South Platte River Basin, Colorado.

Other conjunctive use optimisation models include Chaolunbagen and Xue Fenghai, Liu Zhaoyi and Ma Wenzheng, and Pei Yuan Sheng, all in *Wuhan 1988.*

Weller (1990) developed a farm model to simulate the viability of conjunctive use for the Porac irrigation scheme in the Philippines where groundwater is used as an insurance against the failure of surface water supply. The model computes the break-even crop yield per hectare for a range of farm sizes from 0-18 ha at levels of conjunctive use of 100%, 70% and 40%. Costs and aquifer characteristics are included in the model (transmissivity is taken to be 1,700 m^3/d, as measured at the project). At 100% conjunctive use, the optimum farm size was found to be 2 - 2.5 ha, requiring a yield of 3.6 tonnes per hectare to be viable. With lower levels of conjunctive use the range of optimum farm sizes increased and the necessary yield to achieve viability decreased. Overall the model was found to reflect the pattern of development of conjunctive use very well where very small and very large farms were found not to be viable for 100% use of groundwater. The larger range of viable farm sizes for lower levels of conjunctive use is attributed to farmers reluctance to adopt the more expensive supply.

Water quality models may be used to estimate the salt concentration associated with different combinations of groundwater and canal water, and the effect of different pumping rates on groundwater quality. For example, Attia (in AIT, 1990) considers the integrated management of surface and groundwater quality with respect to land reclamation in the Nile valley. Government policy restricts the use of Nile waters for new reclamation. Therefore reclamation of 40,000 ha is planned using tubewells conjunctively for irrigation and drainage in the flood plain, and for irrigation in the desert fringes. A model was used to estimate the likely build up of salts (Ca, Mg, Na, K, HCO_3, SO_4, and Cl) from groundwater pumping.

The model estimates changes in the salt concentration of groundwater over time for different pumping rates by simulating processes of convective transport, hydrodynamic dispersion, and mixing (dilution) from pollution sources. It is estimated chlorides vary from 9 mg/1 for a 4 m drop in head to 21 mg/1 for 19 m drop in groundwater head. The relationship between pumping, heads and changes in salt concentration indicates that groundwater cannot be used on its own to irrigate the desert fringes because of falling heads and salinisation. On the other hand groundwater pumping alone causes large increases in salt concentration. The optimum is a mix of 25% surface water and 75% groundwater. However, as surface water is in short supply it is proposed to use treated sewage water which is believed to be technically and economically feasible because the land is generally within 8 km of towns and cities and there are problems disposing of sewage effluent.

(b) Planning Models

O'Mara and Duloy (in O'Mara, 1988) describe a family of models developed by the World Bank and transferred to WAPDA in Pakistan for the rational planning of conjunctive use. A simulation model links the hydrology of a conjunctive use system, a network model of river and canal flows, and an economic model of agricultural production. 53 regions are represented by the model as irregular polygons with distinct boundaries. The polygons are linked by groundwater underflows over which the surface water network is superimposed.

Each polygonal model has embedded in it a single farm production system model which includes resource allocation choices facing an individual farmer for 11 crops and 4 livestock commodities. Decision variables are rainfall, evapotranspiration, and pumping from public tubewells. Private tubewell pumping and canal supplies are treated endogenously by the model for policy evaluation purposes. The optimising model maximises farm income less a risk premium term. The model allows for crop specialisation to meet farm family consumption needs and regional comparative advantage.

Explicit assumptions contained in the model are that aquifer withdrawals and returns are in balance - the only links between polygons are underflows (i.e. there are no economic links) and prices are constant for grain and cash crops. In addition the model incorporates implicit assumptions of projected world prices, the elimination of distortions in agricultural pricing and water allocation, and efficient investments. The use of border prices theoretically removes distortions and is expected to increase value added (at domestic prices) by up to 27% with virtually no effect on agricultural employment. It is also assumed that full utilisation of Pakistan's water resources will be achieved by 1995, and further development will have to come from technical development and higher value crops.

The model predicted that more efficient use of both resources would yield an increase of 17-20% in agricultural output, a 14-16% increase in employment, and an increase in basin-wide output of 200% between 1977 and 1995. That is equivalent to a 34% per capita gain over the period, a growth rate of 1-2% per year. Maximum gains are expected from a combination of more efficient water allocation, complementary investment in drainage in saline areas and the public control of private tubewell withdrawals. The model combines both investment-planning and basin-wide irrigation management using a hierarchal decision making multi-level programming model in which there are policy makers and policy receivers and policy receivers are optimising agents.

Lemoine and Gotsch (1985) developed a closed control model for Arroyo Seco water resources development project in Salinas Valley, California. As above, the model includes an aquifer model which simulates the response of groundwater to pumping or. recharge and an optimisating algorithm which allocates water on the basis of its economic value. However unlike models which iterate between independent optimisations of the economic and hydrologic models, this model integrates the economics of water use derived from an optimisation model of the agricultural sector with the physical movement of groundwater simulated by the hydrological model. By solving in a single step optimal water use among regions over time, externalities related to the interdependency of pumpers in the various sub areas as they seek to exploit a common aquifer can be accounted for.

The model suggests overall benefits of collective management of resources to be in the order of 4.5% over a planning horizon of 20 years, a modest increase because although water is the binding constraint in agriculture, it is not sufficiently scarce to induce higher returns to management.

Implementation suffers from the following empirical limitations. The groundwater model assumes the whole aquifer to be confined, and stream-aquifer interactions were simplified in the discharge equations. The pumping cost equations assume that variations in drawdown in a given sub-area during the irrigation season are independent of the pumping and recharge in other sub-areas. Surface water allocation is treated as an exogenous variable and would be better included in the model.

The authors conclude that the model shows socially optimal water allocation is more efficient than private water allocations. However, it is thought that water institutions lack the political or legal mandate to redistribute costs and benefits reorganisation would require. Further, the magnitude of benefits of reorganisation may be insufficient to induce farmers to pay necessary transaction costs.

Under a tank modernisation strategy, Palanasami and Flinn (1988) compared the impact of additional wells with that of sluice modification (lowering the level to increase supply), canal lining, sluice management (closing the sluices for two days when the daily rainfall exceeds 60 mm), and rotational management (closing sluices on alternate weeks). A model was used to simulate water releases from the tank, water allocation to rice crops in different sectors of the command area, and crop yield reductions due to water stress at different stages of crop growth and at different positions in the irrigation system. It was run for different tank storages and levels of groundwater supplementation. It was found canal lining, additional wells, and rotation management reduced production losses by 56 to 66% and increased total rice production by 30-36%. In comparison, sluice management increased production by 14% and sluice modification had a negligible impact on yields. The greatest gains were from combined physical and management improvements.

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