Issues in the Efficient Use of Surface and Groundwater in Irrigation

Gerald T. O'Mara
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ABSTRACT

The efficient use of water resources where ground water and surface water are used conjunctively may require special policies to rationalize the interaction among pumping by farmers, canal diversions by irrigation system managers, and the physical response of the stream aquifer system. The problem is acute in the great alluvial basins of Asia -- the Indus, Gangetic, and North China Plains -- where surface water irrigation has long been practiced and modern tubewell technology has been diffused extensively in recent decades. These alluvial basins account for a large proportion of total irrigated land in developing countries and the countries involved account for about half of the world's population. Significant gains in output are possible from more efficient conjunctive use in such regions (for example, an increase of 20 percent is estimated for Pakistan). However, these potential gains are not costless because their realization requires changes in irrigation institutions, methods of irrigation management, and often accompanying investments in drainage facilities.

Three broad approaches to the problem of efficient resource use under externalities (that is, physical interdependence among individual producers) have been defined by economists: (1) assignment of well-defined, transferrable legal property rights; (2) imposition of corrective taxes or subsidies; and (3) centralized control over the entire resource. The feasibility and institutional implications of these approaches are discussed and several case histories of actual policy responses to the social costs incurred by inefficient conjunctive use are reviewed. The use of more sophisticated analytical methods in coping with the difficult informational and managerial requirements of efficient conjunctive use is assessed. The prognosis is hopeful, but efficient conjunctive use will require much better information systems, more skilled and responsive irrigation managers, and institutional reform that involves water-using farmers more actively.
Pour que les ressources en eaux souterraines et de surface puissent être utilisées simultanément de façon efficace, il peut être nécessaire de mieux coordonner, par des mesures spéciales, les éléments suivants : le pompage effectué par les agriculteurs, les canaux de dérivation contrôlés par les responsables de l'irrigation et le comportement du système formé par les cours d'eau et la nappe aquifère. Le problème est particulièrement grave dans les grands bassins alluviaux d'Asie (Indus, Gange et plaines de la Chine du Nord) où les eaux de surface servent depuis longtemps à l'irrigation et où la technique moderne des puits tubulaires s'est largement répandue au cours des dernières décennies. Ces trois bassins alluviaux représentent une part importante de l'ensemble des terres irriguées dans les pays en développement et les pays où ils se trouvent comptent près de la moitié de la population mondiale. L'utilisation plus rationnelle des eaux souterraines et de surface permettrait, dans ces régions, des gains de production considérables (qui pourraient, par exemple, atteindre 20 % au Pakistan). Toutefois, ce résultat ne peut être obtenu qu'au prix d'une modification des organismes responsables de l'irrigation et des méthodes de gestion de l'irrigation, et moyennant, dans bien des cas, des investissements dans des installations de drainage.

Les économistes proposent trois formules permettant d'utiliser efficacement les ressources en eau compte tenu de certains facteurs extérieurs (notamment de l'interdépendance des différents producteurs) : 1) octroi de droits de propriété officiels bien définis et transférables; 2) imposition de taxes ou de subventions à des fins d'ajustement; et 3) contrôle centralisé de l'ensemble des ressources en eau. Le présent document examine si ces solutions sont applicables et analyse leurs répercussions au niveau des institutions. Il examine aussi les mesures effectivement prises dans plusieurs cas d'espece pour faire face aux coûts sociaux résultant de l'utilisation inefficace des eaux souterraines et de surface. Puis il évalue les méthodes analytiques plus élaborées employées pour résoudre les délicats problèmes d'information et de gestion qui se posent lorsque l'on tente d'utiliser ces eaux simultanément et de façon rationnelle. Les perspectives sont encourageantes, mais pour parvenir à ce résultat, il faudra améliorer considérablement les systèmes d'information, trouver des responsables plus compétents et plus dynamiques, et procéder à des réformes institutionnelles assurant une participation plus active des agriculteurs.
Cuando las aguas superficiales y subterráneas se utilizan conjuntamente, el uso eficiente de estos recursos puede requerir la racionalización de la interacción entre las actividades de bombeo por parte de los agricultores, la desviación de las aguas a los distintos canales según lo determinen los administradores del sistema de riego y la respuesta física del sistema acuífero. El problema es grave en las grandes cuencas aluviales de Asia --la del Indo, el Ganges y las planicies del norte de China-- donde no sólo se riega desde hace tiempo con aguas superficiales sino que en los últimos decenios se ha difundido mucho la moderna tecnología de los pozos entubados. A estas cuencas aluviales les corresponde una gran proporción de total de las tierras de regadío en países en desarrollo y aproximadamente la mitad de la población mundial vive en los países a los que pertenecen dichas cuencas. Es posible lograr mejoras significativas de la producción con un uso conjunto más eficiente en dichas regiones (por ejemplo, se estima un incremento del 20% en el caso de Pakistán). No obstante, estos posibles aumentos acarrean ciertos costos porque para lograrlos se necesitan cambios en las instituciones pertinentes y en los métodos de administración del riego y, con frecuencia, inversiones conexas en sistemas de drenaje.

Los economistas han definido tres enfoques generales para el problema de un uso eficiente de recursos en los que hay influencia de factores externos (es decir, interdependencia física entre cada uno de los productores): 1) asignación de derechos de propiedad bien definidos y transferibles; 2) imposición de gravámenes o subsidios correctivos, y 3) control centralizado de la totalidad del recurso. Se examinan la factibilidad y las repercusiones institucionales de estos métodos y se revisan varios ejemplos de respuestas de políticas para los costos sociales que produce un uso conjunto ineficiente. Se evalúa el uso de métodos analíticos más complejos para hacer frente a los difíciles requerimientos de información y administración que implica un uso conjunto eficiente. El pronóstico es prometedor, pero un uso conjunto eficiente requerirá sistemas de información mucho mejores, mayor capacitación y flexibilidad de los administradores del riego y una reforma institucional que abarque una participación más activa de los agricultores que utilizan el agua.
Summary and Conclusions

This paper both distills the discussion and provides relevant background on the ideas examined at the Workshop on Externalities in Irrigation (WEI), held at the World Bank, May 11-13, 1983. The genesis of the Workshop was a growing concern with the effects of externalities (i.e., physical interdependence in production between farmers) on the efficiency of water allocation in the irrigated agriculture of developing countries. When the usual assumption of physical independence in production between different producers is not valid the well-known arguments for the efficiency of the market allocation of resource do not hold. While some economists have elaborated schemes that would permit a market allocation of water resources to be efficient, the conditions required for this result are restrictive; and in practice water resources are developed and operated under public sector management in almost all countries. Unfortunately, experience has shown that the existence of public sector management does not assure efficiency, and this conclusion applies a fortiori when physical interdependence complicates both the policy guidelines and the structure of incentives required for efficiency. In general, both the management and incentive problems impeding efficient allocation are greatest when groundwater is an important source of supply. The purpose of the workshop was to examine some of these hard cases, particularly those involving the joint (i.e., conjunctive) use of surface and groundwaters, in order to discern which policies and incentive structures were most successful in achieving efficiency.
For historical reasons related to the evolution and diffusion of modern tubewell technology, large scale utilization of groundwater for crop production is a relatively recent phenomenon (i.e., since 1960) in developing countries. In contrast, large scale utilization of surface water in irrigation is much less recent, having been practiced for thousands of years in some developing countries. The largest tubewell investments to utilize groundwater have occurred in the great alluvial basins of Asia where surface water irrigation has long been employed -- e.g., the Indus, Gangetic and North China Plains. In such areas, which account for a large proportion of total irrigated acreage in developing countries, significant opportunities for output gains from more efficient use of surface and groundwaters have been created by the recent development of large scale capacity to exploit groundwater reserves, e.g., O'Mara and Duloy estimate a gain of 20 percent is feasible in Pakistan. However, these potential gains are not costless since their realization requires changes in irrigation institutions, methods of irrigation management and often enabling investments in drainage facilities. In succeeding paragraphs, summaries are given of the obstacles to more efficient conjunctive use, the experience of conjunctive use in several major agricultural regions, and some new analytical methods of managing more efficient conjunctive use.

The Problem of Market Failure

The essence of the failure of efficiency in the market allocation when physical interdependence (i.e., an externality) is present is that costs as seen by private agents differ from social costs. The major reason for this failure in the case of water resources is apparently common
(i.e., non-exclusive) nature of water in an aquifer or stream. The several remedies proposed by economists to redress the market failure are 1) assignment of transferrable, well-defined legal property rights such that the span of physical effects coincides with legally recognized responsibility, e.g., can individual well-owners be held liable for payment of compensation to other well-owners whose costs have increased due to the former's pumping? 2) Corrective taxes or subsidies that are just sufficient to adjust private costs to the level of social costs; and 3) centralized control over the resource embodying the externality so that a single management will fully internalize the external effects in its calculation of costs. The legal rights solution tends to be preferred by economists since in theory these will be traded until a market equilibrium is reached with private costs equal to social costs and without the necessity of government intervention. However, the fugitive nature of water makes well-defined legal rights difficult to specify for complex stream-aquifer systems. Moreover, most legal systems have difficulty in defining legal rights in such a way as to capture the span of physical effects. The tax or subsidy remedy demands measurement of the cost of the externality, which is technically feasible, and has proved workable in California. Centralized control has been applied to numerous oil fields but successful applications to stream-aquifer systems are virtually unknown. This approach in effect requires private producers to recognize the costs due to their collective behavior and accept central control in their collective interest. Whatever the institutional solution to the problem of externality that is chosen, historical evidence suggests it will be most difficult to implement unless no current user suffers a decrease in his water allocation, i.e., it is Pareto-safe with respect to existing allocations.
In addition to the preservation of water rights based on precedent, other principles of quasi-legal allocation found to be important constraints to allocation were distributive justice, symmetry of losses and symmetry of sources. Distributive justice requires that allocation not violate the irrigating society's accepted canons of equity and symmetry of losses specifies that the burden of adjustment to large variations in water supply should be shared. Symmetry of sources, which is concerned with social cost, specifies that water rights should cover all sources, with appropriate allowance for differences in cost and characteristics. This principle is not universally accepted but is essential to efficient conjunctive use of surface and groundwaters.

Guidelines for efficient utilization of surface and groundwaters can be in conflict with some of the principles of quasi-legal allocation. One guideline states that efficient spatial use of surface water requires equalization of marginal products across farms and regions when measured at a common reference point (e.g., rim station). Another guideline specifies that efficient intertemporal operation of a pure aquifer system requires equalization of discounted marginal products across time periods when measured from a common reference point (e.g., well-head). Finally efficient operation of a stream-aquifer system requires equalization of discounted marginal products of surface and groundwater across space and time when measured from a common reference framework. Large opportunities for efficiency gains are available in theory from this last guideline, which is very commonly violated. Water rights based on precedent but lacking in fungibility will often result in violation of the first guideline, while the second is often violated when access to an aquifer is treated as an appurtenant to the land.
Since access to water is crucial to income and subsistence in water scarce regions, farmers in such areas naturally prefer to have some say over the disposition of the available water. However, nominal authority for allocation in even medium-sized systems is invariably vested in irrigation systems managers. Moreover, the information requirements for efficient centralized control of an irrigation system of significant size are formidable; and large centralized systems, such as those of south Asia, often most delegate significant autonomy to district engineers. The conjunction of significant discretion in the hands of relatively low level functionaries and the desire of farmers for local control tends to result in significant rent-collecting by the functionaries. It seems evident that institutional change permitting greater farmer participation in water allocation would both limit the exposure of the irrigation bureaucracy to moral hazard and provide useful feedback from the group most knowledgeable about actual crop water requirements.

Institutional Solutions to the Problem of Efficient Conjunctive Use

A review of the experience of the state of California in the USA in coping with externalities in aquifer and stream-aquifer systems was found relevant to the developing countries because of the state's long experience with such problems. Parts of California have experienced all of the cost increasing effects of aquifer externalities -- increased groundwater pumping lifts and costs, additional investments in well deepening and pump lowering, land subsidence, decreased water quality, sea water intrusion, and exclusion from aquifer supply of some pumpers. The form of response was mostly local political action, e.g., forming water-users association, voting for public conservation districts with taxing
authority, or legal action over water rights, e.g., adjudication. Many successful solutions involved importing water, often furnished via state and/or federally funded surface water transport systems. Proposed action at the state level was defeated by the concerted opposition of water users. The California experience exhibits a common pattern of response, which may be summarized as follows: 1) farmer preference for local control of water, 2) ultimate recourse to control over pumping and use of a pumping tax, and 3) the facilitating role of water imports in formulating Pareto-safe policies.

Pakistan attempted to implement the centralized control approach to achieving efficiency in a stream-aquifer system (i.e., the Indus Basin). This experiment must be deemed a failure in that the government never achieved control of groundwater pumping. Instead, the demonstration effect of government tubewells induced a massive and still continuing boom in private tubewell investments. At present, the private share of tubewell pumping in Pakistan is 75 percent and growing. Moreover, effective government control over the aquifer in the saline groundwater areas, where private tubewell investments do not payoff, has been negligible due to the absence of facilitating drainage investments. However, there is evidence that the Government of Pakistan is now taking action to achieve control over the aquifer in the saline groundwater areas. Control over the aquifer is not yet necessary in the fresh groundwater areas, but it is likely to become a critical requirement for efficient management in the future. A careful analysis disclosed the following reasons for the failure of the government tubewell program:
1) engineering and design problems, 2) operating and maintenance problems, 3) lack of unified management at the local level, 4) lack of effective supervision of well operators, and 5) lack of planning for watercourse level organization. More generally, it may be concluded that the program presupposed the existence of a management structure and skills that did not exist in the irrigation bureaucracy at the time.

In contrast to the attempt by Pakistan to internalize the costs of externalities by means of centralized control of the surface and groundwaters of the Indus Basin, China has followed a decentralized policy of local control in the North China Plain. Individual communes were encouraged to invest in tubewells (by means of an investment subsidy and technical assistance on drilling), and in the 1960s and 1970s, over two million shallow, small capacity tubewells were constructed. Much of the Plain is a water deficit area in the sense that mean precipitation is less than crop requirements. Thus, agricultural development in this water scarce region has depended on irrigation, mostly through small scale storage and canal investments (pond, shallow lakes, deep trenches, weirs across small rivers, etc.). The tubewell boom of recent decades greatly augmented available storage, permitting the multiple cropping index to rise from 132 in 1952 to 157 in 1979. The area irrigated by groundwater is now double the area irrigated by surface water -- there are very few areas with access to both sources. Particularly in the drainage area of the heavily silt-laden Yellow (Huang) River, Chinese practice has been to cycle surface waters through the shallow aquifer to tubewell fields beyond the reach of canals, whose range for direct surface irrigation has been kept limited.
This minimizes both the problems of silt deposition and costly redundancy in water delivery systems. In contrast to the ingenuity shown at the local level, there is apparently no overall management of basin-wide water resources; and, indeed, the institutional basis for such management seems to be lacking. There are reports of the effects of externalities similar to those reported elsewhere in the world: falling water tables, land subsidence and wells going out of service. Injection wells are now used to control land subsidence, and there are advocates of controls over exploitation of the aquifer system. Given the decentralized nature of existing practice, recourse to a tax (or subsidy when required) on pumping would seem to be an obvious choice for a method of control.

Analytical Methods for Managing Efficient Conjunctive Use

Two of the three remedies proposed by economists to redress the market failure induced by an externality, corrective tax (or subsidy) and centralized control, clearly require analytical methods for managing efficient conjunctive use. The third remedy, well-defined legal rights, also requires the use of analytical methods for determining those rights such that the aquifer is managed efficiently on the part of someone duly authorized by the legal system. Thus, the existence of analytical methods capable of providing the basis for managing the complex interdependence in stream-aquifer systems is a necessary condition for efficient conjunctive use. Fortunately, such methods have been developed in recent years. These methods all stem from advances in the parallel revolutions in mathematical modelling and digital computation of the past several decades. The ongoing development of ever less costly and more powerful computer hardware makes
it certain that this technology will be extended ultimately to nations at all levels of development. The only real constraint to this diffusion is human skills and this is a removable constraint.

The number of applications of the new analytical methods has snowballed in recent years, including contributions from and collaboration between a variety of disciplines, e.g., geohydrology, economics, civil engineering, operations research. Recently joint simulation and management models have been developed, and professional opinion has focussed on this approach as preferred. A combined model considers the particular behavior of a given groundwater and/or agro-economic system and searches for the best operating and investment policy under the objectives and constraints defined by political leadership and irrigation management. Studies which link aquifer, farmer response and management decision can be classified into two major classes: i) hydraulic management models, and ii) policy evaluation and allocation models. Models aimed primarily at managing groundwater stresses such as pumping and recharge are included in the first class. Models which simulate the behavior of economic agents, where the environment includes complex groundwater-surface water interactions and specific institutional content are included in the second class. Although these models are not explicit policy selection models, they can be used to evaluate policy alternatives.

Applications of policy evaluation and allocation discussed include the modelling of the Indus Basin of Pakistan and the Mendoza region of Argentina. Both applications derived estimates of optimal taxes to equate private with social costs and redress the market failure. Other
examples considered included the effects of interaction between surface irrigation and well pumping on farmer incentives to invest in tubewells, the effects of externalities due to exploitation of pure aquifer systems on food security alternatives in arid regions, and institutional and investment design of efficient conjunctive use in India.

Conclusions

The difficulties in achieving efficient conjunctive use discussed in this paper tend to be problems of middle-aged irrigation systems in alluvial basins. Such difficulties will eventually surface in over half the irrigated areas of the world. They are already painfully evident in three great alluvial basins, the Indus and Gangetic Plains of South Asia and the North China Plain, that are dominant in the irrigated agriculture of three nations accounting for close to half of the world's population.

The concept prevalent in the 1960s that government could easily coordinate pumping and canal diversions by keeping control of both in state hands has been superceded by the reality of farmer (or production team) control of pumping in the major alluvial basins reviewed. It is now apparent that a feasible conjunctive use plan must recognize not only farmer insistence on Pareto-safe water allocation policy but also the farmer objective of some control over the water allocation process. Since farmer participation will inevitably require cooperation among farmers, the need for development of water users associations becomes a first order priority. Another clear if obvious proposition is that farmers (and bureaucrats) will only seek a remedy when they believe a remedy exists. This implies that neither group will accept proposed solutions whose mode of action is beyond their understanding. For this reason, irrigation professionals have a
responsibility to communicate in clear language to all concerned parties those technical results which can be used to significantly improve irrigation efficiency. One such result is the size of the gains that are possible with efficient conjunctive use. A related result is the information and skill intensity of the methods required to achieve this objective. It will require changes in the methods of irrigation management and irrigation institutions in order to implement a monitoring and control system which can adapt efficiently to changing physical conditions. Moreover, in many environments, efficient conjunctive use is not feasible without prior enabling investments, e.g., drainage, and this condition must be communicated to both farmers and irrigation managers if political support for these investments is to be created and sustained.
# Table of Contents

<table>
<thead>
<tr>
<th>PREFACE</th>
<th>xix</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chapter I. INTRODUCTION</strong></td>
<td>1</td>
</tr>
<tr>
<td>Some Important Concepts</td>
<td>2</td>
</tr>
<tr>
<td>Diffusion of Tubewell Technology</td>
<td>6</td>
</tr>
<tr>
<td>Importance of Sustainable Policies</td>
<td>7</td>
</tr>
<tr>
<td><strong>Chapter II. INSTITUTIONAL CONSTRAINTS TO EFFICIENT MANAGEMENT OF A STREAM-AQUIFER SYSTEM</strong></td>
<td>9</td>
</tr>
<tr>
<td>Market Failure Due to Physical External Diseconomies</td>
<td>9</td>
</tr>
<tr>
<td>Equity in Water Allocation</td>
<td>17</td>
</tr>
<tr>
<td>Guidelines for Efficient Water Allocation</td>
<td>22</td>
</tr>
<tr>
<td>Preference of Farmers for Local Control</td>
<td>27</td>
</tr>
<tr>
<td><strong>Chapter III. SOME INSTITUTIONAL SOLUTIONS TO THE PROBLEM OF EQUITY-CONSTRAINED EFFICIENT CONJUNCTIVE USE</strong></td>
<td>30</td>
</tr>
<tr>
<td>The Heterogenous California Path</td>
<td>30</td>
</tr>
<tr>
<td>The Evolving Pakistani Experience</td>
<td>37</td>
</tr>
<tr>
<td>The Difficult Chinese Path to Efficient Conjunctive Use in the North China Plain</td>
<td>50</td>
</tr>
<tr>
<td>Resources and Agricultural Production in the North China Plain</td>
<td>50</td>
</tr>
<tr>
<td>Conjunctive Use in the North China Plain</td>
<td>53</td>
</tr>
<tr>
<td>Review of Policy Responses to Externalities in Conjunctive Use</td>
<td>59</td>
</tr>
<tr>
<td><strong>Chapter IV. SOME ANALYTICAL METHODS FOR MANAGING EFFICIENT CONJUNCTIVE USE</strong></td>
<td>62</td>
</tr>
<tr>
<td>A Brief Review of Groundwater Modelling Methods</td>
<td>63</td>
</tr>
<tr>
<td>Finding an Acceptable Policy</td>
<td>67</td>
</tr>
<tr>
<td>An Application of Multilevel Policy Evaluation and Allocation Modelling</td>
<td>68</td>
</tr>
<tr>
<td>Measurement of the Costs Due to an Externality</td>
<td>74</td>
</tr>
<tr>
<td><strong>Chapter V. SOME ANALYTICAL RESULTS WITH RESPECT TO EFFICIENT CONJUNCTIVE USE</strong></td>
<td>76</td>
</tr>
<tr>
<td>Dynamic Conjunctive Use to Minimize Income Fluctuations</td>
<td>76</td>
</tr>
<tr>
<td>Cases Where Water Resource Externalities Forced Policy Re-examination</td>
<td>78</td>
</tr>
<tr>
<td>Case Study of Planning for Conjunctive Use</td>
<td>79</td>
</tr>
</tbody>
</table>
Chapter VI. SUMMARY .................................................. 82

References ................................................................. 87
Appendix A: Papers Presented at Workshop on Externalities in Irrigation .................................................. 89
Appendix B: List of Participants at Workshop on Externalities in Irrigation.................................................. 90
Appendix C: A Glossary of Technical Terms Relating To Management of Stream-Aquifer Systems............... 92
Preface

The major sources of ideas and inspiration for this paper was a Workshop on Externalities in Irrigation (WEI), held at the World Bank, May 11-13, 1983. Lists of papers presented at the workshop and participants are appended to this paper. However, in order to bring the issues discussed at the workshop to the attention of a broader audience, that part of the international development community concerned with agricultural development, I have introduced background material from other sources and have shaped the discussion to focus on this fundamentally pedagogical objective. In consequence, readers desiring a more in-depth exposure to the ideas presented are referred to the papers presented at the workshop. For the present, these may be obtained from the author of this paper. A conference volume is expected to be available at a later date.
I. **Introduction**

Application of irrigation waters to permit crop production in arid and semi-arid regions dates back to the dawn of the neolithic agricultural revolution (about 6,000 B.C.). However, the intensive development of water resources toward greater agricultural development on a virtually global scale is of relatively recent origin, i.e., the last century. Not until progress in engineering practice had reached the point that structures could be placed astride quite sizeable rivers was it possible to extend perennial canal irrigation to large, alluvial basins. Similarly, not until efficient and compact engines and pumps were developed could groundwater resources be exploited on a significant scale. These developments have made possible quite large scale agricultural development in certain water short basins, e.g., the Indus Basin, the North China Plain. Now that the limits of water resource endowments are being reached in many such regions, the developmental emphasis has shifted toward achieving more efficient utilization of these scarce resources.

In particular, research in irrigation has focussed attention on the potentially large gains from efficient joint use of surface and ground waters in those large alluvial basins, e.g., Gangetic Plain, Indus Basin, North China Plain, where physical interdependence between these water resources complicates the allocation problem. For example, O'Mara and Duloy (WEI) estimate a 20 percent output gain is feasible in Pakistan from more efficient conjunctive use. A closely related problem is the loss of resource productivity and environmental deterioration that comes with sustained irrigation development that neglects the need for removal of salt accumulations in confined or slowly draining alluvial basins.
A. Some Important Concepts

This paper will review the several approaches to the resolution of these problems that are in actual use and will consider some schemes for more efficient utilization of water resources that have been proposed but not implemented as yet. In order to convey to the reader the technical complexity of the problem of efficient management of conjunctive use in a surface-ground-water system, some preliminary discussion of essential concepts will be useful. Readers who wish to refer to a glossary for definitions of technical terms used in the discussion can find it in Appendix C.

A groundwater aquifer may be visualized as a giant sponge that is buried underground. Water that is absorbed by the soil at the land surface above the giant sponge will (after some evaporative losses) seep downward by the force of gravity to be stored in the sponge after reaching either an impermeable boundary or a volume of water already stored, i.e., by reaching the groundwater table. Water may also move horizontally in the sponge if it is subjected to a gravitational or hydraulic force vector in that direction, i.e., underground transmission. Water may also enter and leave the sponge horizontally—i.e., underflows deriving from subsurface sources or sinks that connect with the aquifer boundary. If the groundwater level in the sponge rises close to the surface, evapotranspirative (ET) withdrawals will become significant. Undisturbed by human intervention, a groundwater aquifer will tend to reach a steady state in which the change in storage over a sufficiently long period is zero. The main adjustment mechanism is changes in the groundwater level which vary ET losses so as to

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1/ This discussion is in terms of an important special case, primarily in order to focus attention on some important physical linkages. It is possible for an aquifer to be confined in several dimensions, so that natural recharge either is from distant sources or is non-existent. For such aquifers, ET withdrawals are either negligible or non-existent. Multiple aquifers in several strata separated by impermeable barriers also occur.
achieve a kind of stochastic steady state. If the inflows from seepage and underflows is almost negligible, then outflow from ET and underflows must be negligible and the aquifer is essentially an exhaustible resource, e.g., the deep aquifers of desert regions. In the more typical case, inflows are significant, and the watertable is likely to be fairly close to the surface if outflows from ET and underflows are to match inflows in the statistical sense. Since alluvial aquifers in large river basins are usually quite large and typically contain many times the annual inflows, a relatively small adjustment in watertable level may be sufficient for them to accommodate the large positive or negative recharge of exceptional years. Alluvial aquifers are clearly renewable resources for which the prudent yield is mean long term recharge.

The introduction of surface water irrigation in a river basin with an alluvial aquifer disturbs the previous stochastic equilibrium. Since canals will leak and not all irrigation water applied will go to crop consumption, an increase in inflows via canal and field seepage will occur. Thus, mean recharge becomes positive, and the watertable commences a secular rise, which ends when increased withdrawals from ET match the increased flows. By the time this has happened, the watertable is probably so close to the surface that significant waterlogging and salinization of soils is noted. This process may take decades or just a few years, depending on environmental factors and the pace of development. If

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2/ A stochastic steady state is an equilibrium that exists only in terms of the long run average and periodic observations will differ from the long run average due to random (i.e. stochastic) variation.

3/ Mean long term recharge is average annual recharge, exclusive of net pumping, where the average is taken over enough years to obtain a tight confidence interval on the estimate of population mean.

4/ This is the same as a stochastic steady state. Cf Footnote 2.
groundwater quality is adequate for cropping, drainage of the excessive accumulation of secular reserves may be realized by using tubewells as a supplementary irrigation source. If the groundwater quality does not meet cropping standards, then pure drainage is probably required. However, mixing with incoming canal water may preserve an irrigation use for at least some of the excess water stored in the aquifer.

Interdependence between ground and surface water supplies means that the levels of efficient controls on groundwater withdrawals depend on the allocation of surface water. While this allocation is typically controlled by the government, the quantity to be allocated in any one season is stochastic. The dynamic, stochastic nature of the problem affects the behavior of both the government officials allocating supply and the farmers utilizing irrigation supplies. The ability to efficiently manage joint utilization of ground and surface water supplies permits policies that both decrease exposure to risk and increase significantly mean agricultural production. The stochastic nature of naturally occurring flows makes it desirable on efficiency grounds to define the safe yield in a long term statistical sense which permits greater withdrawals in time of drought to minimize the impact on agricultural production, with restoration of the mined quantities occurring during periods of greater than normal flows. Where some areas in an alluvial basin do not have access to good quality groundwater, as happens in the saline groundwater areas of the Indus Basin, then it is possible to divert a greater proportion of the diminished naturally occurring flows in drought years to such areas. Areas with access to good quality groundwater will then in such years depend on tubewell pumping for a greater proportion of water supply Unfortunately,
the simple fact is that the efficient use of secular reserves in the aquifer to smooth out the effect of fluctuations in naturally occurring flows on agricultural production is very rare.\footnote{Secular reserves are the volume of water that can be withdrawn from the aquifer (i.e., mined) without severe environmental damage.} While hydrologists and systems engineers have known that more efficient use of groundwater is possible for some time, a more comprehensive specification of the problem that encompasses the institutional, legal and political constraints has yet to find general acceptance.

"Rational treatment demands that systems engineering be based not so much on the methodologies sometimes mistaken for system engineering but on a broad, scientifically firm foundation encompassing the very nature of the system concerned, historically, politically, legally, physically, productively, technically and economically."\footnote{Hall and Dracup, p. 3-4.} This quotation from a water systems engineer accurately states the nature of the problem. However, in practice, as a review of the literature on conjunctive use problems demonstrates, there is a strong tendency to treat legal and institutional factors as outside the system. In this respect, a political scientist notes "...water planners and engineers, in search of constraints to simplify their task of system design, have found it convenient to read inflexibility into governmental institutions and to treat them as immutable, if irrational, restrictions. On the contrary, there is and should be considerable flexibility in legal and administrative forms, which are quite adaptable in the face of demonstrated economic, technological, social or political needs."\footnote{Arthur Maass in Maass et. al., p. 565.}
Diffusion of Tubewell Technology

Historically, the development of the technology of surface water irrigation preceded the development of tubewells based on compact diesel or electric power sources. In fact, the introduction of tubewells in the Indus Basin and perhaps the North China Plain was motivated by concern over waterlogging and salinization due to rises in the water table induced by canal irrigation. The demonstration effect of public drainage wells set off tubewell investment booms by individual farmers (in South Asia) and individual communes (in north China). In Pakistan, the number of tubewells increased from less than 5,000 in 1960 to over 200,000 by 1980. In the Indian states of Punjab and Haryana, the total by 1980 was over 400,000 wells (of somewhat smaller capacity). In the Gangetic plain of India, it is estimated that more than 2 million shallow, low capacity private tubewells have been installed. In the 1960s and 1970s over 2 million small capacity tubewells were installed in North China. These massive investments in tubewells have completely transformed the utilization of water resources in these regions and pose issues of resource management that exceed the grasp of existing irrigation bureaucracies. For example, in the Indus Basin of Pakistan, tubewells now supply over one half of the water actually available for crop consumption in the fresh groundwater areas. Of course, tubewells supply none of the water for crop consumption in the saline groundwater areas (about one third of total irrigated land of the basin). However, the bureaucracies concerned with distribution of surface water supplies do not attempt to achieve an efficient joint allocation of surface and ground water supplies; and, in fact, the legal basis for an attempt to do so is unclear and open to challenge.
While the existence of massive investments in tubewells poses a challenge to resource management to which the concerned bureaucracies have been unable to respond adequately as yet, these investments are also a necessary pre-condition to a regime of efficient conjunctive use of surface and ground waters. Thus, once the governments of these regions do meet the challenge, a significant improvement in water productivity and agricultural output can be achieved.

**Importance of Sustainable Policies**

The evolution of irrigated agriculture in major alluvial basins from inundation to modern perennial canals to the tubewell explosion of recent decades traces the interaction of human society with the environment in arid/semi-arid regions. As the scale of development increases, the pressure on the natural resource base increases and the environment is changed in significant ways by human intervention. The introduction of modern perennial canals induces positive net recharge to alluvial aquifers forcing a rise in the water table until increased ET losses establish a new equilibrium level. The required level of ET losses is very likely to push the watertable so close to the surface that significant waterlogging and salinization occur. By undertaking certain facilitating investments, e.g., drainage works, the productivity of the salinized and waterlogged lands can be restored. The point is, the initial investments changed the state of the system, requiring further investments to alter the state of the aquifer system to one more conducive to human welfare. Proper appraisal of the initial investments would have recognized that intervention would change the state of the system and subsequent investments were really a necessary complement to the initial investments. Unfortunately, such
foresighted appraisals are quite rare in the history of irrigation. In the past when the scale of development was much lower and many countries had unexploited resources, such myopic investment planning while inefficient did not present intolerable choices to future generations. At present, fewer countries still have unexploited resources; and most developing countries can no longer tolerate myopic planning which fails to adopt strategies and policies that are sustainable in the sense of bequeathing to future generations a resource base whose productivity is unimpaired.
II. Institutional Constraints to Efficient Management of a Stream-Aquifer System

A. Market Failure Due to Physical External Diseconomies

In the microeconomic theory of industry supply, an important determinant of supply sometimes consists of effects external to the firms providing supply but internal to the industry. These external economies or diseconomies, or externalities in brief, affect the cost functions of individual firms as the output of the industry changes. Externalities are classified as "pecuniary" and "physical" (or "technological"). For a pecuniary externality, the interaction between industry output and firm costs comes about solely through changes in input prices. For a physical externality, the interaction is through industry output effects that directly operate on the physical production possibilities of the firm.

Interdependence through water supply is such a classic example of physical externality that it is used illustratively in many economic textbooks. For example, farmers who jointly depend on a common aquifer have interrelated costs. If some farmers pump their tubewells sufficiently to lower the watertable in the vicinity of their neighbors' wells, the increased lift with its increased energy cost will increase the average and marginal costs of production of the neighboring farmers. If the drawdown is sufficient to put wells out of service, the required investment in deeper wells will further increase costs. Thus, "overpumping" by some farmers imposes a physical external diseconomy on their neighbors.

Conversely, if a situation of positive recharge leads to waterlogging and salinization of soils, then "overpumping" by some farmers may lower the costs of their neighbors through the improved yields (for given variable
inputs) that come from the improvement in soil productivity due to a lowered watertable. In this instance, "overpumping" or mining of the aquifer leads to physical external economies for neighboring farmers.

The importance of physical externalities is that they lead the "invisible hand" of the market mechanism astray by driving a wedge between private and social costs, i.e., the private agent does not recognize as a cost the effect of his actions in raising or lowering the costs of others. This is certainly true of the pumping decisions of individual well owners. Another example much used by textbook authors concerns firms depending on the same river (in serial fashion) for water supply. Viewed as a productive input, water as a commodity has dimensions that include place, time, quality and degree of certainty of supply. Thus, if an upstream user is free to discharge an effluent back into the river after degrading its quality, downstream users who need a level of water quality not met by the water polluted by the upstream user will suffer an increase in costs as they either expend resources to purify the polluted water or seek more expensive alternative sources. Once again, the problem is that the cost to the downstream user is not recognized by the upstream user, who supplies his output at a price that does not reflect its true social cost. Thus, a physical externality has long been recognized by economists as a potential source of failure of markets to achieve an efficient resource allocation.

It has been suggested that the term "externality" contributes nothing to analytic insight and the terms non-exclusive and/or non-rival describe the essence of the failure of the market mechanism to deal with the phenomena subsumed under the rubric of externality. Clearly, it is the
non-exclusivity of groundwater resources and the technical difficulties to assigning meaningful property rights (i.e., exclusivity) to ground water that constitutes the essence of the externality among groundwater users (Randall, WEI). However, this paper shall follow accepted practice in the economics profession and use the term externality to assign a label to the phenomenon of non-exclusivity that lies at the heart of the matter.

Since physical externalities represent sources of social gain or loss that are not reflected in market signals to private agents, economic theorists have considered various possible remedies. Mainstream economic analysis has focused on the following solutions to the problem: (i) corrective taxes or subsidies that add a penalty or reward to private agents just sufficient to adjust private costs to fully reflect social costs; (ii) centralized control over the resource embodying the physical externality so that a single management will fully internalize the external effects in its calculations of costs—e.g., "unitized" operation of an oil field, with individual well (or land) owners receiving pro rata shares of overall profits; and (iii) assignment of legal property rights so that the span of actual physical effects always coincides with legally recognized responsibility. This last solution tends to be preferred by theorists since it minimizes the need for state intervention. It has been generalized into a proposition known in the literature as Coase's Theorem: Given well-defined initial legal property rights and zero transactions costs, the market allocation will be efficient. The argument establishing this result has affected private agents offering payments to owners of
legal rights either to or not to exercise these rights depending on whether the cost of the externality is negative (i.e., a benefit) or positive. In the resulting market equilibrium, with the price of say non-exercised rights driven to equality with the marginal cost of the externality, private costs are equal to social costs.

The problem with actual application of Coase's Theorem, is the limiting assumptions required to establish this result. Legal rights must be well-defined and transactions costs must be at least small relative to benefits. Perhaps the most serious drawback is the elusive nature of "well-defined" legal rights when physical interdependence is in any way complex. Less serious but also troubling is the fact that the cost of the required legal services is usually small in relation to benefits only when the benefits are absolutely large.\(^8\) Thus, in a pure surface water irrigation system, the comparative simplicity of the physical interdependence has permitted precise definition of legal rights in the form of the doctrine of prior appropriation, or rights based on historic use. That is, earlier users have preference over late users. This means in times of low natural flow, the rights of senior users have precedence over those of junior users, who may in fact receive no allocation in such circumstances. Note that often such rights are usufructs and may be lost if not exercised. Since water rights are legally well-defined in this simple situation, they are marketable (if sale of rights does not undermine the legal rights of the seller); and junior users are free to negotiate for temporary purchase of rights from senior users. If the value of a unit of

\(^8\) Knapp and Vaux present evidence from California which indicates that "fifteen years is not an inordinate period for the settlement of ground-water litigation and the costs of adjudication can run as high as $76 per acre-foot of annual groundwater use."
water is greater to the junior user, he will be able to offer a price that exceeds its value in use by the senior user; and a mutually beneficial transaction will occur. In this fashion, the marginal value of water is equalized among users (after allowing for transmission losses and transaction costs) and an efficient allocation can be achieved. It should be observed that this scenario is rarely followed in actual practice. That is, water rights are usually not legally defined in such a manner as to permit transactions in rights that are encompassed by legally enforceable contracts. Moreover, the "use it or lose it" nature of many legal rights provides a perverse incentive to use water inefficiently.

However, once a more complex physical interdependence is introduced in the form of an alluvial aquifer, the precise definition of legal rights becomes problematical. For instance, tubewell pumping that lowers the watertable adjacent to a streamflow will induce increased seepage to groundwater or interrupt return flows to the stream, with the result that downstream flows are reduced to the detriment of the holders of appropriated surface flow rights downstream. Thus, where groundwater is an unrestricted common property resource (as it is in Pakistan and still largely is in the Western U.S.), a very junior upstream user who invests in a tubewell can obtain an implicit senior right over downstream users. In response to litigation stemming from such a context, the Supreme Court of the State of Colorado ruled that groundwater (with certain exceptions) would eventually reach the surface stream and thus was subject to the prior appropriation doctrine. In consequence, well-owners with junior rights cannot pump unless all senior rights holders downstream have satisfied
their rights. In contrast to the previous situation which placed a zero value on these costs, the court has placed an infinite value on these costs. In a simulation study of the Colorado case, Daubert and Young found either extreme situation was grossly inefficient, and that efficient resource management required both joint use and an appropriate price for the externality.

Clearly, a working market in transferable water rights would allow upstream well-owners to purchase rights from senior holders downstream and by setting a market price for the externality produce an improvement in efficiency of resource use. Note that the gain comes from treating surface and groundwater symmetrically. This implies establishing pumping rights on the same basis as rights to surface water. It implies further that water rights are fungible irrespective of source. However, it should be noted that the hydrologically sensible principle of symmetry of water sources specified implicitly by the Colorado court is not accepted in almost all other jurisdictions.

The principle of symmetry of water sources, i.e., water is water, would seem to be fundamental to either efficient or equitable conjunctive management of surface and groundwaters. For example, consider the dynamic use of the secular reserves in the aquifer to smooth out the impact on agricultural production and rural welfare of abnormally low natural flows in an alluvial basin in which only some farmers have access to good groundwater. How can this be accomplished unless well-owners pump more

Note that this requirement forces the well-owner to get a waiver of assignment of rights from all downstream senior rights holders before a transaction transferring rights is valid. This is an impossible requirement and defeats the mechanism which validates Coase's Theorem.
water and accept lower relative surface water allocations? Clearly, it is not possible to utilize total water resources efficiently if surface and ground waters are segregated into separate compartments.

In addition, it is important to note that a workable market in transferable water rights requires that sellers be able to transfer title to a given quantity of water with certainty and this is often possible to only a limited degree with many irrigation systems. For example, in the warabandi rotation system of South Asia, water course deliveries are passive consequences of diversions to distributory and minor canals, where such diversions are rotated among a number of such canals from flows along major or branch canals. For this system, rights transfers can be effected with certainty only along a water course, and even here the amount of water transferred remains uncertain.

More generally, the introduction of supplementary groundwater supply via private tubewells destroys the simplicity which facilitates well-defined legal rights specified by Coase's Theorem. Some form of conscious management would seem to be necessary. In addition, private tubewells have in the context of surface-ground-water irrigation an agricultural significance that goes beyond this complication. A tubewell can supply water on demand, and this capacity permits use of tubewell supplied water to (1) eliminate risks from failure or inadequacy of canal

10/ For a good description of the Warabandi system, see Reidinger or Van der Velde.

11/ Gisser argues that the market can perform efficiently in a stream-aquifer system, at least in the case of the Pecos Basin of New Mexico. However, his argument presumes assignment of exclusive water rights by a state engineer. This is conscious, public interest resource management and not the operation of the invisible hand.
supply, (2) augment water supplies for greater cropping intensity--e.g., a second crop cycle per year with a secure water supply, and (3) optimize water inputs over the cropping cycle to secure larger yields. The risk reducing effect of tubewell supply also induces greater use of other yield-enhancing inputs--e.g., fertilizer. However, tubewell water is available on demand only when the farmer controls the well. Thus, when tubewells are introduced into a region with usable groundwater, significant investments in private tubewells are probable. Note that the farmer's incentive for such investments is increased profit and decreased risk. Any drainage effects of his tubewell pumping are neglected by him since these are negligible for any one farmer. Moreover, even if he controls his pumping for environmental reasons, his neighbors have an incentive to "free ride" by pumping more so long as the marginal revenue exceeds the marginal cost of pumping. A probable outcome when tubewells are highly profitable is pumping in excess of net inflows, i.e., negative recharge. Sustained mining of the aquifer will eventually lower the watertable to the point at which many wells go out of service. At this point, either artificial recharge (via collective action) or investment in deeper and more costly wells with greater energy costs is required to sustain tubewell water supply. Eventually, even if the deeper wells are built, sustained mining will totally exhaust an aquifer.

The failure of the preferred solution of well-defined, legally enforceable property rights in the absence of public interest restraint on well pumping to achieve efficiency or even equity in contexts with interdependence due to reliance on a common aquifer leaves the centralized operation and tax-subsidy alternatives as prospective remedies. However,
public or private schemes to manage aquifer operation cooperatively suffer from the disadvantage that individual agents have an incentive to cheat and detection of cheating is difficult since the well-owner is free to choose the occasions on which he pumps—e.g., in the dead of night. Taxation of pumping also suffers from the same agent incentive to cheat. Public ownership solves the problem of cheating, but introduces an even greater problem. Control of the wells is now out of the farmers' hands and entrusted to the discretion of a large number of low level (and often poorly paid) public employees, and this circumstance provides a multitude of opportunities for rent-seeking behavior on the part of the tubewell operators. In simple consequence, publicly owned tubewells have acquired an evil reputation and are widely conceded to be an inferior solution to the problem (in the sense that large inefficiencies in groundwater utilization are seen to be inevitable).12/

B. Equity and Legality in Water Allocation

In an arid or semi-arid environment, water is the factor input that determines the scale and intensity of agricultural production. In an agrarian, pre-industrial society, control over the essential input to agricultural production determines the social class structure and income distribution. This input usually is good agricultural land, but in an arid environment it is control over water that determines which land will be farmed and the intensity of cropping. Thus, in an arid environment, control over water is equivalent to control over income and wealth, to say

12/ See Johnson (WEI) for an illuminating discussion of the administrative problems attendant to the large scale introduction of public tubewells in Pakistan.
nothing of survival. For this reason, the mechanism for allocating water in agrarian societies situated in arid regions is intensely political and is typically sanctioned by institutions dominated by the ruling elite. In fact, this is usually the case even in industrial societies located in arid environs. It follows that any significant change in the water allocation mechanism must meet with the approval of the ruling elite, at least when not accompanied by bloody revolution. Therefore, the basic principle of all institutional mechanisms for implementing improvements in water utilization and water resource conservation is that existing allocations must not be reduced—in the language of welfare economics, the improvement must be Pareto-safe. In practice, this proposition usually assumes a somewhat different form, which might be called the first principle of equitable water allocation:

1. **Principle of Prior Appropriation.** Sustained historic access to irrigation water confers property rights enforceable by either law or custom and tradition. These may be lost with sustained disuse.

   Note that the statement of this quasi-legal principle says nothing about source, transferability, or association with other attributes (e.g., water and land linked as a productive unit). It can be and often is extended to order of priority so as to cope with the stochastic character of naturally occurring flows. However, other distributive arrangements may fix proportionate shares of available supply, turns in a circle, reserved time in a rotation, seasonal allocation, crop priorities or saleable water
rights. The common feature is that all such arrangements are invariably based upon precedent—historic water use.13/

Now the first principle is backward-looking and Pareto-safe. It says nothing about future increments to irrigated water supply resulting from development of water resources through public investment or better public management. This prospect is a great interest in many developing countries in arid regions, and is covered by:

2. **Principle of Distributive Justice.** Allocation of uncommitted water resources should not violate the accepted canons of equity for the irrigation society.

The reader quite naturally will tend to interpret this principle in terms of the rules of equity that characterize his values—e.g., allocation of uncommitted water should not worsen the distribution of income or blatantly discriminate against any minority. However, it specifies only that the canons of equity for the irrigating society be observed; and this might entail distributing the water entirely to some preferred group such as the ruling class. Since water can be made fungible, such an action is not necessarily inconsistent with efficient utilization of the resource.

Since water allocation norms must cope with the stochastic character of natural water flows and the variation in these can be so great as to threaten the stability of the society, a rule for this situation is needed:

13/ For a discussion of water distributive arrangements, see Maass and Anderson, especially chapter 9.
3. **Principle of Symmetric Losses.** The burden of extreme stochastic variation in total water supply should not be placed asymmetrically on a subset of users.

While it might be argued that the power structure of a society would operate so as to shift disproportionate burdens to those with least power, it should be recalled that the degree of variation in supply is specified as great enough to threaten the stability of the society. Under such a condition, only a society in process of sustained dissolution would permit gross asymmetry of burden.

Lastly, but by no means least, there is a strong need when water is scarce and valuable to reconcile the norms of custom and/or legality with economic efficiency in such a way that efficiency is not badly impaired. This need is particularly strong in developing countries, and is met by the following rule:

4. **Principle of Symmetric Treatment of Sources.** Rationalization of rights to water resources with efficient resource utilization requires that rights be specified in terms of water of common characteristics *per se*. That is, rights should cover all sources, with appropriate allowances for differences in cost and characteristics. Rights need not be identified with a source.

The reader may have noted that this last principle is somewhat different in its thrust from the preceding three, which are concerned with the stability and continuity of the irrigating society. The last principle is concerned with reconciling economic efficiency with the prevailing value system of the irrigating society. Hence, it presupposes that economic welfare is a significant value to the society. Where this condition is not met, the last principle will be rejected.
The four principles equitable of quasi-legal water allocation enunciated above are sufficient to cope pragmatically with equity problems in a variety of cultural contexts so long as scarcity of water exists and an abiding concern for the stability of the society motivates the leadership.

Note, however, that the formal expression of these principles is in the provisions of the laws of the irrigating society that apply either explicitly or implicitly to the use of water and the development of water resources. This "water law" is the basis for setting administrative rules and regulations concerned with water resource allocation and development. As an expert on water law observed:

"The underlying philosophy of each particular system of water law has a direct connection to the surrounding physical factors of its origin. Where water is plentiful, regulation is aimed at ameliorating the harmful effects of water (floods, salinization, etc.), but, where water is scarce, regulation is aimed at ensuring an adequate supply, for example, by providing that water is not owned by one individual by, rather, collectively so that all may use what is available.

"Over time, distinct regional or national systems emerged which reflect particular physical conditions and social goals. Elaborate water laws and administrative systems evolved where the greatest needs and most serious natural constraints existed. Through adoption or imposition many of these systems have also influenced or directed water use and control in other countries or regions. Although retaining many of the basic characteristics of the original system, modifications have been incorporated to meet indigenous conditions."
"Systems may be classified into three categories: customary, traditional, and modern. 14/ Two customary systems (Islamic and Hindu Bali) reflect the philosophy of life in the areas where they are practiced. Traditional and modern systems blend with each other and will be discussed together. The traditional systems reflect the length and thoroughness of traditional codes. There is much variation in the modern codes and laws. They range from defining the theme of the code as set out in policy with emphasis either on public interest or economic forces of the marketplace, to an analytical approach with emphasis upon the dynamic nature or failure of the law and the changes that have or ought to occur." (Radosevich, WEI, p.88)

C. Guidelines for Efficient Water Utilization

In the previous discussion of physical externalities, the physical interdependence among farmers utilizing tubewell water from a common aquifer was discussed at length, as was the physical interdependence among users along a stream with respect to water quality. However, there is another form of interdependence among users along a stream; and in this instance, the externality is pecuniary. Suppose the users along a stream are partitioned into upstream and downstream users, and some water is taken from downstream users and given to upstream users. The increase in water available to upstream users lowers the opportunity cost of water as

14/ This classification was adapted to analyze the eight major systems described at the International Conference on Global Water Law Systems, Valencias, Spain, Sept., 1975. For a thorough discussion on the various water law systems, see Proceedings of the International Conference and Global Water Law Systems, Vol. 1 to 4, Prepared by G. Radosevich, et. al., Colorado State University, Fort Collins, CO. (1976).
perceived by these users, inducing more water intensive cultivation, increasing gross agriculture supply for a given level of output prices. ¹⁵/ That is, when water allocation to a region is increased, the value of its marginal/product (the appropriate input price for the farmer) drops for all of the farmers, lowering costs across farms and inducing an increase in gross output. ¹⁶/ Note that the pecuniary external economy is induced by the action of the public agency allocating water supply along the stream. Of course, if the additional water is taken from another region, as was hypothesized, then a reverse effect, or a pecuniary external diseconomy, is induced in the region losing water. These two opposed effects need not cancel out, given a fully utilized water endowment. If the value of the marginal product of water in the gaining region is greater than the value of the marginal product of water in the losing region, the effect on agricultural output will be positive. Since water is seldom allocated by a market, there is no presumption that the value of the marginal product of water is equalized across regions and gains from re-allocation of water are typically possible among users along a stream. Moreover, if the increased allocation of water comes from an increase

¹⁵/ Strictly speaking, this is only true if the shadow price to the farmer is also the social opportunity cost. This may not be true if the farmer is induced to expand output of a heavily subsidized crop. In such cases, the change in gross output is social welfare terms may be negative.

¹⁶/ Since almost universally water charges are subsidized and water supply is allocated by non-market means, water users typically are not in an equilibrium such that the value of the marginal product of water is equal to the water charge. Rather farmers allocate their given water allocation so that the value of the marginal product of water is equalized across crops at a given point in time. Since there is no assurance that water can be costlessly stored, the marginal value product of water is not necessarily equalized over time even on the same farm.
increase in total diversion for irrigation, or from diversions that achieve better efficiency in delivering water at a time and place it is demanded, then it is possible for all users along a stream to benefit. Opportunities for such Pareto-efficient gains are not as rare as they should be.

To summarize this discussion, several basic propositions on efficiency in water utilization will be presented. Before that is done, it will be useful to define a standard commodity unit of water. Our definition of a standard commodity requires that the water commodity be distinguished by location, time, quality and probability of supply. If two quantities of water differ in any of these characteristics, they are different commodities. Note that different water commodities often can be transformed into the same commodity, although perhaps with some loss in transformation. For example, transporting otherwise equivalent quantities of water to the same location will transform them into the same commodity; but there will be losses to seepage and evaporation during transport. Similarly, different water commodities can often be substituted for another within limits. For example, water that is too saline for crop use by itself can be mixed with water of better quality and in that fashion be utilized for cropping. Thus, rates of exchange between different water commodities can be established. When discussing water utilization, it is convenient to use a standard water commodity, but it should be understood
that the argument generalizes across water commodities by means of rates of exchange between them. 17/

The basic propositions on efficiency in water utilization, which assume no risk aversion by policymakers and are to be interpreted in terms of the expected values for stochastic quantities, are as follows:

Proposition 1: The standard water commodity is the same, whatever the source.

Proposition 2: Efficient spatial operation of a pure surface water irrigation system requires that the social opportunity cost of water, i.e., the value of its marginal product at efficiency prices, at a common source (i.e., rim station) be equalized across farms and regions at each point in time. 18/

Proposition 3: Efficient intertemporal operation of a pure aquifer irrigation system requires that the discounted social opportunity cost of water at the well-head be equalized across time periods.

Proposition 4: Given the optimality of preserving the productivity of the resource, renewable aquifer resources have an efficient mean annual yield equal to mean annual recharge.

Proposition 5: Efficient operation of a joint surface-ground-water irrigation system requires that the discounted social opportunity cost of surface water equal the discounted social opportunity cost of groundwater across farms and regions at each point in time. Both social opportunity costs must be measured from a common reference point, e.g., field level.

17/ Note that the rate of exchange may be zero if substitution is not possible; and where substitution is possible, the rate of exchange may change discontinuously when a bound is reached.

18/ A rim station is a flow measurement point at which a river carrying runoff from the mountains enters the plains of an alluvial basin.
These propositions can be derived heuristically in the manner of the discussion above on pecuniary external economies, or more formally using a model. Proposition 1 is trivial; but in water resource utilization, for historical reasons, it is necessary to explicitly state the obvious. Proposition 2 converts all water units to a standard commodity and thus is really a standard proposition on efficient static allocation of any one period input. Proposition 3 is simply the well-known Hotelling result on efficient allocation of an exhaustible resource. Proposition 4 is the necessary condition for a sustainable policy with respect to a renewable aquifer resource. Proposition 5 generalizes proposition 2 to the conjunctive use case. Since both its proof and its implementation in practice require dynamic utilization of secular reserves, neither proof nor practice is simple. It can be proved using non-linear programming or optimal control methods.

The reader will note that each of the efficiency propositions is commonly violated in actual irrigation practice. For example, many waterlaws treat surface and ground waters as separate, distinct categories, thus violating proposition 1. Where the principle of prior appropriation is applied to water allocation, typically the rule of proposition 2 does not hold. Due to physical externalities, it is often the case that the exploitation of pure aquifer systems deviates from what proposition 3 specifies. Similarly, earlier discussion has already noted that propositions 4 and 5 are often not descriptive of actual practice, although in the long run, proposition 4 has to hold if the productivity of the resource is to be sustained. The obvious moral to all this is that there exist significant opportunities to reap output gains from improved
utilization of irrigation waters. The skeptic may well respond to this assertion by asking "If there are so many opportunities for unrealized gains, why have not either private agents or governments acted to realize them?" The answer to that question involves several points: a) Both governments and private agents naturally prefer to first exploit easily realized opportunities, and historically in many regions this has been possible. b) Many of the possible gains in efficiency involve institutional change that either is not or is perceived not to be Pareto-safe, and thus conflict among interested groups prevents adoption of the output improving institutional changes. c) Many of the potential gains require significant investments as a necessary condition for realization, e.g., large scale drainage, and other investments have seemed to be more attractive to governments in the past. Now that some of the more obvious and easily realized gains have been exploited in many countries, the less obvious or apparently more difficult system wide gains constitute the frontier for improvements in water resource productivity.

D. Preference of Farmers for Local Control

Since access to water is crucial to income and subsistence in water scarce regions, farmers in such areas naturally prefer to have control over the disposition of the available water. As previously noted, the apparent certainty of control over groundwater supply that a private tubewell brings is a powerful inducement to a farmer for a well investment. The control over water supply that a tubewell brings can often increase farm income and decrease exposure to risk. This combination of advantages usually more than offsets the higher cost of water and the perceived risk of well failure due to collective overpumping by
well-owners. Hence, the introduction of tubewell technology tends to set off a tubewell investment boom.

Similarly, farmers dependent on surface water or public tubewell supply prefer to have control over these supplies. While it is not possible to achieve individual control as in the case of private tubewells, some control can often be achieved via collective action. There is much to be said for local control by farmers since they have the most to gain from efficient water allocation and are the best informed with respect to water requirements, local hydrology, etc. Moreover, the information requirements for efficient centralized control of an irrigation system of significant size are formidable and actual practice tends to fall palpably short of maximal efficiency. In fact, large centralized systems, such as those of South Asia, often must delegate significant autonomy to district managers and engineers. As the work of Robert Wade has documented, the conjunction of significant discretion in the decisions of relatively low-level functionaries and the desire of farmers for local control tends to result in significant rent-collecting by the functionaries. That is, farmers are willing to pay for some degree of control over the disposition of available water, and the functionaries are willing to accept payment in return for allowing farmer participation in decisions over water allocation. Of course, the farmers would prefer a less costly route to some control over their own destiny, but they usually must deal with the political and administrative environment as they find it. This characteristic pragmatism of farmers in their drive for control over water was considered by Maass and Anderson to be an important finding of their study of irrigation systems:
"The most powerful conclusion that emerges from the case studies is the extent to which water users have controlled their own destinies as farmers, the extent to which the farmers of each community, acting collectively, have determined both the procedures for distributing a limited water supply and the resolution of conflicts with other groups over the development of additional supplies. With important variations to be sure, local control has been the dominant characteristic of irrigation in these regions, regardless of the nationality or religion of the farmers, the epoch, whether formal control is vested in an irrigation community or in higher levels of government, the forms of government at the higher levels, and perhaps even the legal nature of water rights. In this realm of public activity...formal centralization of authority, where it has occurred, has not meant substantial loss of local control de facto. General administrative, legislative, and judicial norms laid down by higher authorities have not negated customary procedures. The norms have been either too general to accomplish this or they have been ignored by local organizations."19/. This quotation somewhat overstates the extent to which local control is achieved in large irrigation systems—Maass and Anderson studied only relatively small systems—but accurately reflects farmer preference for control over the water supply so crucial to their welfare and their related determination to achieve some control by whatever means they can.

Moreover, it is true that farmers are better informed about crop water requirements than an irrigation bureaucrat or engineer. It follows that a system responsive to farmer demand is far more likely to achieve an efficient allocation than any system which pre-supposes superior information and decision-making capacity on the part of the irrigation bureaucracy, and neglects feedback from farmers.

III. Some Institutional Solutions to the Problem of Equity-Constrained Efficient Conjunctive Use

A. The Heterogeneous California Path

Although California is one of the most developed regions of the world, the early development of groundwater utilization there and the variety of the resulting institutional responses provide instructive lessons for groundwater development in the developing countries. The relatively recent history of large scale groundwater exploitation in developing countries (i.e., within the last three decades) prevents finding experience similar to California among the developing countries.

It is important to realize that much of California is a natural desert, with average annual rainfall of less than 15 inches throughout most of the southern part of the state. In the arid parts of the state, early development of agriculture depended on private investment in surface water canals utilizing runoff from the mountains and the groundwater aquifers of the valleys and coastal plains. Later, the great urban areas of the state (e.g., Los Angeles, San Francisco) obtained water supplies at long distance by means of large public investments in aqueducts, and this set the pattern for later large scale state and federal investments. However, in 1950, one half of the water supplies for 7 million irrigated acres were still from groundwater. Between 1950 and 1980 rapid population growth (116%) and significant expansion of irrigated acreage (38%) resulted in a 121% increase in net water use. Almost all of the increase came from increased use of surface water, which was often transported long distance.

20/ This section is based on the paper by Coe (WEI).

21/ An interesting description of early irrigation development in the San Joaquin Valley is found in Maass and Anderson.
as the aquifers of the state suffered increasingly from severe overdrafts. Since 75% of the runoff in California occurs north of Sacramento, while 75% of water use occurs south of Sacramento, large scale investments for water transport were necessary. By 1980, 76% of water supplies were from surface water. Total groundwater usage actually increased slightly in the 1950-1980 period, but groundwater supplies were not adequate to meet the large increase in demand.

In fact, throughout recent decades, the effects of over-exploitation of groundwater have forced farmers and other local interests to consider solutions to deal with the adverse effects of overdraft. "In California, permits and licenses are not required for use of groundwater as they are for surface water. Any overlying landowner can drill on his property and pump water unless the water rights have been adjudicated by the Courts. Groundwater is considered to be appurtenant to the land and the right to its use is analogous to a riparian surface water right."

The combination of rapidly growing demand for water and an early lack of public concern over the external diseconomies from uncontrolled pumping produced the expected adverse effects.

1. Increased groundwater pumping lifts and costs.
2. Well deepening and pump lowering.
3. Land subsidence.
4. Decreased water quality, including sea water intrusion.
5. Exclusions from aquifer supply of some pumpers.

22/ COE (WEI), pp. 2-3.
As the effects of overdraft became apparent, a groundswell of response by users typically emerged. "In those areas where overdevelopment and detrimental effects occurred, it was normal practice for those experiencing problems to create a water association to provide a forum for discussion. Usually consultants were retained to provide advice. When a plan had been agreed upon and it was necessary to levy taxes, condemn property, or contract to import water, a public agency was created. In some cases the groundwater rights were adjudicated in order to equitably allocate the scarce groundwater resource. However, adjudication of water rights does not provide additional water. The importation of supplemental supplies has been the solution to overdraft whenever it has been feasible." In order to examine the California experience in detail, Coe presents case histories for four areas. Each of these will be briefly discussed.

**Santa Clara Valley**

This is an area of some 500 square miles south of San Francisco Bay, with average annual rainfall of 13 inches. Water-bearing sediments extend to a depth of 1,000 feet. Prior to World War II, this area was largely agricultural, producing fruits and vegetables. Large scale urbanization occurred subsequently, and the population of the area is now 1.4 million persons. "Historically, groundwater was the principal source of water supply, with many flowing wells. In 1949, the Department of Water Resources estimated the overdraft was 52,000 acre-feet per year. Observations of groundwater levels indicate this value increased after this

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23/ COE (WEI), pp. 3-4.
The initial overdraft was caused by agricultural users. Eventually the increase in land values and urban pressures led the farmers to sell their property to developers, and the agricultural valley became a small megalopolis. The groundwater table has dropped 120 feet since 1910, with most of the decrease occurring before 1950. This induced significant land subsidence, with a drop of 13 feet recorded at the point of maximum decrease. The drop in the groundwater table also produced intrusion into the aquifer of sea water from San Francisco Bay and connate brines from the neighboring hills. The user response to these adverse effects initially was the formation of the Santa Clara Valley Water Conservation District (1929), which was a forum for discussion of possible solutions. Before long the discussion moved forward to action and by 1955, the conservation district had constructed 10 dams to store waters for later release to groundwater recharge. Later when it became clear that local water resources were fully developed, surface water was imported, using water available from state and federal projects. When it also became clear that control over groundwater pumping was required, a pumping tax was imposed. In 1983, this tax was $54 per acre-foot to municipal and industrial users and $13.50 per acre-foot to agricultural users. To halt sea water intrusion, an intrusion barrier was built, using injection wells and treated waste water.

24/ ibid, p. 5.
25/ ibid., p. 5.
Coastal Plain of Los Angeles

This is an area of 420 square miles southwest of central Los Angeles. Prior to World War II, the area was a mixture of agriculture and oil production and refining activities. Agricultural crops were vegetables, fruits and cut flowers, with groundwater as primary source of water. Subsequently, very rapid urbanization sharply increased water demand, with water supplies coming from groundwater overdraft and imported water from the Colorado River. Population of the area now exceeds 3 million people.

Due to overpumping, the groundwater table dropped more than 100 feet below sea level in the 1940s, and sea water intrusion occurred. In response, two water user associations were created, West Basin (1946) and Central Basin (1950). Later, two municipal water districts were created to permit levying taxes, West Basin (1947) and Central Basin (1952). Somewhat later, local interests decided that adjudication of groundwater rights was needed. The Court decrees (in 1961 and 1962) limited extractions and appointed the state department of water resources as manager. To prevent sea water intrusion, a barrier was built in the 1950s, using injection wells and imported water.

Orange County Coastal Plain

This is an area of about 300 square miles south of Los Angeles with an average annual rainfall of 13 inches. Before World War II, the area was agricultural, producing citrus fruits and vegetables. After the war the area rapidly urbanized, and population is now 1.9 million persons.
Overdraft in the agricultural era caused the groundwater table to drop 10 feet (forebay) to 23 feet (pressure area) below sea level, inducing sea water intrusion where geological conditions permitted. User response was the creation of the Orange County Water District (1933). Currently, about 100 thousand acre-feet of water is imported annually for recharge, and a sea water intrusion barrier has been constructed, using both injection and extraction wells. To provide finance for imported water, a pumping tax was levied. The tax is now at $15 per acre-foot. Rejecting adjudication, local interests have adopted a water utility concept that prices water from all sources the same and user supply is guaranteed.

Kern County

This county, which covers 6,840 square miles, is located in the southern San Joaquin Valley. The Kern River crosses the country and is the main source of additions to the aquifer. Average annual rainfall is 7 inches, and depth of water-bearing sediments is as much as 4,500 feet. There is an upper unconfined aquifer and a lower confined one, which is the principal source. Irrigation commenced with diversions from the Kern River around 1900, but after introduction of deep well drilling and pumping methods in the 1940s, groundwater became the main source of supply. The county remains agricultural to this day, and had 944,000 irrigated acres in 1980, of which 780,000 overlay a groundwater aquifer. Overdraft has caused the groundwater table to drop 200 feet, significantly increasing pumping and well construction costs. In addition, over-exploitation has induced about 10 feet of land subsidence as well as water quality degradation.
Evidence of a net water deficit in the area has been long accumulating; and starting in 1955, Kern County has received imported water from the Central Valley Project via the Friant-Kern Canal. In 1961, the Kern County Water Agency (KCWA) was formed and later 15 water districts were created as members of KCWA. The state agreed to deliver a firm 1.1 million acre-feet annually plus any available surplus starting in 1968. Recharge occurs from unlined canals and from spreading imported waters on the Kern River fan. KCWA reports that additions have exceeded withdrawals from the aquifer by 1.1 million acre-feet since 1976-77, and an innovative "banking" concept was initiated in 1982, which aims at dynamic conjunctive use. That is, storage in the aquifer can be depleted in times of drought, when surface water imports are low, to be replenished later when surplus imports are available.

To provide finance, a pumping tax was initiated in 1975. In 1982-83, the tax was $10 per acre-foot for agricultural users and $20 per acre-foot for all other users. While current overdraft has been eliminated, the accumulated deficit is still large and subsidence continues. There is yet another important environmental impact which has been neglected. Kern County is in a confined basin, and the imported water brings dissolved salts, which are steadily accumulating. A master drain is an authorized element in the State Water Project, but to date local interests have been disinclined to pay their share of its costs.

Statewide Response to Groundwater Overdraft

A number of legislative proposals to control groundwater statewide have been defeated by concerted opposition from water interests. In consequence, an initiative on groundwater management was placed on the ballot for direct submission to the voters in 1982. This referendum was
also defeated, largely as a result of strong opposition from water interests.

The California experience clearly illustrates the external diseconomies and equity constraints previously discussed and a common pattern of response emerges:

1) The strong preference of farmers for local control of water supplies;
2) The ultimate recourse to control over pumping when a concerned local community of water users has had time to confront the problem of over-exploitation and consider the alternatives;
3) The facilitating role of water imports in formulating Pareto-safe policies; and
4) The common recourse to a pumping tax.

B. The Evolving Pakistani Experience

Although use of surface waters for irrigation in the Indus plains of Pakistan has been going on for millenia, the large scale use of irrigation dates from the development of perennial canals supplied from low wiers or barrages across the Indus and its tributaries, commencing in the 1860s. The distribution across the plains of large quantities of waters that formerly had flushed down the rivers to the sea disturbed the dynamic equilibrium of the natural drainage system, as seepage from tens of thousands of miles of leaky canals caused an enormous increase in recharge to the groundwater aquifer underlying almost all of the basin. This change induced a secular rise in the groundwater table that had generated
widespread salinization and waterlogging of the soils by the time the problem first attracted significant policy attention in the late 1950s and early 1960s. Using funds from US AID, a demonstration project for vertical drainage using public tubewells was initiated in 1960 and completed in 1963. At the time, the newly formed Water and Power Development Authority (WAPDA) of Pakistan and its international consultants were engaged in formulating a program to eliminate waterlogging and salinity. In addition, the American President, John F. Kennedy, after discussion with President Ayub Khan of Pakistan sent a panel of experts headed by Professor Roger Revelle of Harvard University to study waterlogging and salinity in Pakistan. In 1963 the World Bank at the request of the President of Pakistan appointed a group of three consulting firms called Irrigation and Agriculture Consultants Association (IACA) to study the problem and review the proposals by WAPDA and the American White House Panel. Reports of the three firms were incorporated in the Indus Special Study published by the Bank under the authorship of Lieftinck et al. in 1968. The various reports by the several expert groups differed on a number of significant points, e.g., the appropriate level at which the groundwater table should be stabilized, but they all agreed on the need for horizontal drainage (to remove salt accumulation) in the long run, and on the efficiency of vertical drainage by means of public tubewells in the intermediate run. An exception to the general drift of expert opinion was Dr. Ghulam Mohammad of the Pakistan Institute of Development Economics who argued that public tubewells should be installed only where the groundwater was too saline for direct use by farmers. However, in fairness to expert opinion of that era, it should be noted that exploitation of the aquifer via private tubewells
was very rare prior to the 1960s (although use of a more primitive device, the Persian wheel, was common in many areas where the groundwater table was very close to the surface). The demonstration project, SCARP I, did show that the watertable could be successfully lowered by tubewells uniformly distributed over a large area. Apparently it also demonstrated to thousands of farmers that there was usable water a few feet below the surface that could be made accessible on demand for a relatively modest investment in a tubewell. The 1960s and 1970s saw a sustained and still continuing private tubewell investment boom in which the numbers of private tubewells increased from less than 5,000 in 1960 to about 200,000 by 1980.

As yet, there is no clear evidence that the tubewell boom has produced costly and unacceptable decreases in the depth to watertable in the fresh groundwater areas of the basin. However, the tubewell boom has rendered moot the strategy of using public tubewells to control the aquifer in fresh groundwater areas. Control over the aquifer now demands control over the pumping by hundreds of thousands of farmers.

Note, however, that the tubewell investment boom has been confined to the fresh groundwater areas of the basin, which account for about two-thirds of the commanded area. In the other one-third of the commanded area, public control over the aquifer is intact in principle; but a past reluctance to undertake the necessary enabling investments in drainage facilities has nullified potential control thus far.

The failure of the projected public control of the aquifer in Pakistan by means of publicly owned and controlled tubewells is not to be taken lightly. Until the reasons for that failure are thoroughly understood, the public tubewell approach to conjunctive use must be
considered unreliable. In this respect, the review of the SCARP program by Johnson (WEI) is quite instructive. In his review, Johnson identified a number of sources for the disappointing performance of the SCARPs: 1) engineering and design problems, 2) operations and maintenance problems, 3) lack of integrated management at the local level, 4) lack of effective supervision of individual well operators, and 5) lack of planning for watercourse level organization.

With respect to the first source, Johnson notes "due to decline over time of the pumping capacity of the tubewells, submergence of watercourse channel inlets, improperly designed and constructed link watercourses, and under-capacity watercourse channels, actual flows were often much less than the designed supplies."26/

With respect to operations, Johnson notes that "tubewells were designed both to lower the watertable and to provide supplemental irrigation water. In areas where the watertable is very close to the surface, it is necessary to pump the tubewells more in order to lower the watertable. In areas where the watertable is more than 3 meters from the surface, the tubewells can be pumped on demand. Almost all SCARPs followed a pattern of increased groundwater pumping during the initial years and declining groundwater pumping thereafter...With respect to changes in depth to water tables within the SCARPs, these pumping figures result in rapidly falling watertables in the initial years and then rising water tables as quantity pumped declined....Areas in the Punjab with depth to water table less than 3 meters in June 1959 were about 3.8 million hectares and in June

26/ Johnson, op. cit., pg. 160.
1978 covered about 3.9 million hectares.27/ The essence of the operations is the timing of tubewell operation. SCARP tubewells are supposed to be operated on schedules developed by the Irrigation Department. These vary among wells in perennial canal areas, nonperennial canal areas, and uncommanded areas. Schedules do not allow for rainfall, power failures, or personnel problems and therefore must be considered as no more than general guidelines. Poor performance of tubewell operators is one of the main complaints about SCARP tubewells both from farmers and from the Irrigation Department staff. This makes it difficult to determine how many hours each tubewell is operated. Operators are supposed to keep a daily log of tubewell operating hours, but they are frequently absent from the tubewells for long periods and farmers must operate the tubewell themselves, making the log book often only a rough estimate of actual operating hours."28/

However, Johnson also notes that tubewell operation was subject to some arbitrary bureaucratic rules:

"The Irrigation Department has two guidelines for the interagency scheduling committees which meet biannually to schedule tubewell operations in SCARP II: over the year, pumps should run at 40 percent of annual capacity; and on days when pumps are operated, they should run continuously from 12:01 a.m. until 12:00 p.m., with scheduled rest periods between 12 noon and 4:00 p.m. The exact rationale for these guidelines is not at all clear. The first appears to derive from power rationing instituted in 1972 as a result of the war between India and Pakistan. The second guideline

27/ ibid., pg. 164.
28/ ibid., pg. 164-65.
may represent an attempt to pacify tubewell operators whose working hours
ing accordance to official labor legislation are only eight hours, or it may
reflect a mistaken belief in the need to rest the tubewell motors."29/

Operating problems were clearly compounded by unscheduled
maintenance requirements, often due to apparently pre-mature failure of
well components. "Most consultants originally predicted 40- or even
50-year service lives. When it became apparent that the pumping capacity
was quickly declining in almost all of SCARP I and that a number of wells
were facing critical problems with encrustation and corrosion of the
strainers, the consultants first tried to change strainers from mild steel
to stainless steel and fiberglass. It was soon obvious, however, that even
these materials were seriously affected by minerals in the groundwater.
Therefore, the consultants reduced their estimates of tubewell life to 20
or 25 years. In 1971 the Special Committee on the Working of SCARPs set 12
years as the average life of a SCARP tubewell."30/

Despite the significant design and operating problems of the
SCARPs, Johnson argues their disappointing performance can be largely
traced to poor organization and management:

"The planning process, especially planning for management and
administration of the systems, did not attempt to address some of the most
critical issues. Questions related to local level participation in
activities such as construction of link watercourses, organization of
farmers groups;, location of tubewells, and choice of tubewell technology,

29/ ibid., pg. 165.
30/ ibid., p. 168.
appear not to have received sufficient attention by the planners. The fact that operating and maintenance manuals were never prepared for the majority of the SCARPs and that no attempt was made to achieve optimal conjunctive use of canal and tubewell water illustrates that planning was deficient.\(^{31}\)

Since the nominal objective of the SCARP program was to achieve efficient conjunctive use, including in this concept necessary drainage, the latter assertion is a startling disclosure.

"The Panel recommended that the SCARPs be managed as a project under a project management board with the authority to cut across line agencies at the field level. Of the northern SCARPs only SCARP I was organized under a Project Director, but surface irrigation management was under a separate Senior Engineer. In SCARP I the project approach did not succeed, and in 1970 the management structure was changed to a system of separate responsibility for irrigation, agriculture and cooperatives by the respective government departments....One of the problems that plagued SCARP I and certainly was a major problem with SCARP II and Khairpur SCARP was that separate management circles were established for canal irrigation and for tubewell operation. In each case boundaries of the two management circles were different. SCARP II straddled part of the Upper Jhelum Circle as well as falling within part of the Lower Jhelum Circle. Both circles were managed by Senior Engineers and have not direct interaction of lines of authority. Operating SCARPs and canal systems as separate circles practically guarantees that there will be no attempt at integrating...

\(^{31}\) ibid., p. 172-73.
groundwater and surface water use."\(^{32}\) In commenting on what he describes as "perhaps the best managed SCARP" Johnson notes

"Khairpur does monitor depth to groundwater in each well each month and adjusts pumping schedules as needed to maintain a desired groundwater level. Yet even here, as elsewhere, pumping schedules are not adjusted to reflect estimated canal supplies and crop water requirements. In many areas it would be possible to divert canal supplies to water-short commands and to make up for this deficit by pumping extra hours."\(^{33}\) However, Johnson and many other observers agree that the most serious deficiency was in field staff management.

"Tubewell operators comprise the largest number of staff working in SCARP circles. SCARP rules stipulate that the operator must be a local person, but he cannot come from the village or villages served by the well. In order to reduce the danger of misallocation, the rule restricts tubewell operators from working within a radius of 24 kilometers from their place of origin. Yet as the operator is always supposed to be present when the tubewell is in operation, normally 20 hours per day, this rule is clearly counterproductive. It forces the operator to cheat by leaving the system jammed open, thereby circumventing safety devices, or to turn off the tubewell even if water is scheduled. Usually farmers and operators work out some type of compromise which invariably costs farmers money....An additional problem is that tubewell operators are highly unionized and therefore difficult to punish or dismiss. It has also been

\(^{32}\) ibid., pg. 173.
\(^{33}\) ibid., pg. 173.
suggested that another reason why officials find it difficult to control their subordinates is that substantial portion of the operators exactions are passed up the line. Whatever the truth of these allegations, it is clear that day-to-day operations of tubewells are very loosely, if at all, supervised. An absence of effective control over activities of field staff either by senior officials, by standardized cross-checking procedures, or by the farmers through some ability to reward or punish, all demonstrate that planners did not think out how tubewells were to be operated and maintained in practice."

Since the water from SCARP wells was to be used for irrigation, the integration of public tubewells with existing irrigation facilities and organization at the watercourse level should have been foreseen as a major problem in management and social engineering. In this respect, Johnson observes "Tubewells that potentially could serve over 500 hectares and as many as 100 farmers reflect the fact that planners gave little thought to local level conditions. Even the most cursory investigation would have revealed that farmers along a single watercourse had difficulties organizing for operation and maintenance....Provision of large, publicly owned and operated tubewells that were designed to serve two or more watercourses immediately created a potential for all sorts of new conflicts. Investigation of farmers organizational capacities, as well as their technical ability to deal with larger flows of water, would have indicated that smaller capacity, more localized tubewells were better suited to local conditions. The argument that larger public wells are more

34/ ibid., pg. 173-74.
economic than smaller private wells rests on the unproven assumption that management under both systems would be the same. Planners failed to recognize, or ignored, farmers limited capacity to cooperate at the watercourse level as well as the technical difficulties in redesigning watercourse channels to carry higher flows. This was plainly a gross error of planning and goes far toward explaining failures of SCARPs to be utilized properly at the local level. "\(^{35}\)

The conclusion that Johnson reaches from the SCARP experience is that bureaucratic rigidity prevented the adjustments in design and administrative practice that were indicated by the emergence of the problems discussed above. "Failure to change design and operational procedure was primarily a result of the administrative structure associated with large-scale water projects and its relationship to the public decision-making process. The decision to invest in SCARPs and the establishment of priorities for construction were central government decisions, and construction itself was also under the control of a central government organization (WAPDA). Operational responsibility lay with provincial irrigation bureaucracies that had no control over project design and construction. Nor had they historically been actively involved at the watercourse command level where the tubewells actually operate. The situation was further complicated by tubewell operators forming unions and demanding rights that other irrigation employees had never been granted. As the political system discouraged feedback from rural water users and provincial governments did not have the power to influence a rigid public

\(^{35}\) ibid., pg. 174.
decision-making process, it was extremely difficult to change a decision once it was made. International funding agencies must also bear a share of the blame as they were aware of many of these shortcomings, but continued to fund SCARPs without demanding major revisions in either design or management.36/

The obvious lessons drawn from the SCARP program by Johnson are:

1. In selecting a technology, particularly a new one, a system to monitor project implementation is a necessity...
2. Administration of large projects also requires an internal organization to maintain constant project review...
3. Administration jurisdiction must be clearly defined with no areas of ambiguity or overlap...
4. On projects that involve lengthy planning and construction periods, it should be recognized that farmer expectations and behavior change over time...
5. Water pricing and collection policies need to be tied to costs so that users who benefit from the system pay for the services."37

While all of the lessons derived by Johnson would seem to be reflected in current Bank practice, it is perhaps not clear that they were standard practice in the 1960s. More importantly, it is likely that Johnson is erecting implicit standards for performance by irrigation bureaucracies in developing countries that are unrealistic in the sense that they presuppose the existence of management structures and skills that

36/ ibid., pg. 177-78.
37/ ibid., pg. 178.
may not exist. It seems clear that the knowledge required to accurately assess the capacity of the management structure of a given country to respond quickly and flexibly to a variety of stresses does not yet exist. It follows that large projects which often implicitly demand this capacity should be carefully examined for potential management failure at project appraisal.

The story of the SCARPs contains yet another and more subtle lesson. The reader will recall that Johnson noted a failure of the watertable to fall (on average) over millions of hectares served by the SCARPs. This seems surprising when it is noted that not only the SCARP tubewells but hundreds of thousands of private tubewells have gone into service and net abstractions from the aquifer have increased by at least 20 million acre-feet per year. How is this possible when the calculations of the experts in the 1960s anticipated a drop in the watertable despite a gross underestimate of the private tubewell boom? The very simple answer to this question is that expert opinion also underestimated the increase in additions to the aquifer. This miscalculation stemmed from a large error in estimation of the seepage losses from the projected increased in canal diversions upon the completion of Mangla and Tarbela reservoirs, as well as some underestimate of aquifer storage coefficients (which tends to magnify the effect on depth to watertable of a given error in estimation of net recharge). As reported by Lieftinck et al., the 1960s estimate of conveyance losses in watercourse delivery was 10 percent.38/

38/ Lieftinck et al., vol. II, pg. 308.
In the late 1970s, studies of losses along watercourses by WAPDA and Colorado State University indicated that conveyance losses average about 40 percent.39/ Thus, in somewhat over a decade, the best estimates of watercourse conveyance losses increased by a factor of four. Moreover, experiments at WAPDA's Mona Research Station demonstrated that watercourse conveyance losses could be significantly reduced through certain renovation and rehabilitation investments along watercourses. This knowledge found almost immediate application in an ongoing investment program funded by the World Bank. It seems clear, then, that such important system parameters as watercourse loss characteristics not only require empirical verification but also need to be systematically updated as investments (or their absence) and accumulated operations modify system characteristics. This monitoring function is unfortunately often neglected and represents part of the sophisticated information and control system required for efficient conjunctive use.

The Pakistani experience is readily interpreted in terms of the principles of quasi-legal allocation and the guidelines to efficient utilization enunciated in Chapter two. The allocation of water conforms to all of the principles except source symmetry. The available evidence suggests that all of the guidelines for efficient utilization are violated. This result implies a sharp trade-off between quasi-legal allocation constraints and the rules for efficient utilization. With respect to choice of institutional solution, Pakistan, has clearly rejected the centralized control remedy to the market failure occasioned by physical

externalities in water resources. In the Pakistani context, the efficiency tax/subsidy would seem to be simpler to implement than the fungible water rights remedy. However, for at least the medium term future, implementation of a tax/subsidy scheme (or its quota equivalent) is not indicated, since the requisite enabling investments in drainage are not yet in place. Moreover, to be feasible, a tax/subsidy scheme would have to deal with farmers collectively in the form of self-policing water users associations, and the formation of these should be a high priority objective.

C. The Difficult Chinese Path to Efficient Conjunctive Use in the North China Plain.

1. Resources and Agricultural Production in the North China Plain

The North China Plain is the alluvial basin of three major rivers, the Huang (Yellow), Huai and Hai and covers 30 million hectares, of which some 24 million hectares are cultivated. Of the three rivers, the Huang (Yellow) is longest (5460 kilometers) and has the greatest mean flow (56 billion cubic meters), but in some important respects is the least significant. The Huai and Hai have lengths of 1080 and 1090 kilometers respectively and mean annual runoffs of 50 and 29 billion cubic meters respectively. The diminished significance of the Yellow River is due to the extraordinarily heavy load of silt it carries, some 1.6 billion tons in an average year, with most of this originating in the Loess Plateau of the middle reaches. In consequence, large storage reservoirs are impractical in its lower reaches and diversions for canal irrigation onto the North China Plain limited to relatively short canals. Of the enormous sediment
load, approximately 400 million tons are deposited annually on the riverbed of the relatively flat reach across the plain; and over time the riverbed has been lifted and is now four to eight meters above the level of the surrounding plain.40/

The North China Plain, or as it is called in Chinese, the Huang-Huai-Hai Plain has a temperate, semihumid monsoonal climate and highly variable rainfall, which declines from the south (mean of 700-900 mm) to the north (mean of 500-600 mm), with coefficient of variation ranging from 0.5 to 0.8. In addition, potential evaporation does not decrease as steadily from south to north, with a consequent further increase in relative aridity from south to north. Over 70 percent of annual rainfall is concentrated in the monsoonal months of June to September. During the 24 years from 1949 to 1972, flooding was relatively serious in eight years and drought was relatively serious in seven. In an average drought, agricultural output is reduced by one-third, and losses under serious conditions range from one-half to total. The lack of storage capacity on the plain means that much of the precipitation which occurs in the form of storms is not usable for agriculture, though it can and often does create drainage problems. In terms of crop consumption requirements, much of the plain is a water deficit area in the sense that mean precipitation does not exceed crop requirements. Thus, on average, sustaining high yield agriculture on the plain has meant constructing

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40/ Historical records show 1,600 shifts in river courses for the Plain. The Huang has had six major changes in course since 602 B.C., affecting an area from Tainjin in the north to Huaiyin in the South. In a very real sense, most of the Plain can be taken as largely the product of alluvium from the Huang.
access to irrigation supplies, and the history of irrigation in the region goes back millennia. There is archeological evidence of well construction on the plain some 5700 years ago, and over 2,000 years ago the Chinese had begun building dikes to control the rivers. The 1800 kilometer Grand Canal from Hangzhou to Beijing was started around 500 B.C.

The need for supplemental supplies of water and the difficulty of exploiting the water of the Yellow River led to an early interest in developing groundwater supplies. The flat (slope of 1 in 10,000), slow draining basin is underlain in most areas with a shallow aquifer of 10 to 30 meters in depth. In the west of the basin, in the region of piedmont and alluvial fans, there are multiple aquifers, greater thickness and less salinity. Moving east, thickness and number of aquifers decrease and salinity increases. The capacity of the shallow aquifer in fresh groundwater areas has been estimated at 48 billion cubic meters. Modern tubewell technology reached the Huang-Huai-Hai Plain about the same time as it did the Indus and Gangetic Plains in South Asia. In the 1960s and 1970s over two million shallow, small capacity wells were constructed. Total pumpage from the Huang-Huai-Hai Plain was estimated at 27 billion cubic meters in 1978, or 13,500 cubic meters per shallow well per year, and there are reports of numbers of wells running dry in years of severe drought.

The 24 million cultivated hectares of the Plain are about one quarter of the national total, while natural run-off in the region is only 5 percent of the national total. In contrast, the basin of the Chang Jiang (Yangtze) River to the south receives 40 percent of national run-off but has only 24 percent of the cultivated acreage. This mismatch between land and water resources, reminiscent of California, has inspired several
schemes for long distance water transfer similar to those of California. However, as yet, none of them have come to realization.

Grain predominates in the cropping patterns of the plain, but cotton, peanuts, sesame and tobacco are also important. Wheat has the largest area, greatest output and most rapid growth, but maize, rice and potatoes are also well developed. In terms of national totals, the Plain has 46 percent of wheat acreage and 51 percent of wheat output. The large acreage in winter wheat makes possible the extension northward of the multiple cropping area. The Plain has 54 percent of the acreage and 51 percent of the output of cotton, and it produces 60 percent of total output of peanuts and sesame. A cropping cycle of three crops in two years has consistently prevailed over most of the region (i.e., 60-70 percent). The main rotation is winter wheat - summer soybeans (or sweet potatoes or millet) - winter fallow - spring maize (or sorghum or sweet potatoes). In areas where conditions are favorable to intensification, double cropping (e.g., winter wheat - summer maize) or a rotation of five crops in three years are practiced. The multiple cropping index increased from 132 in 1952 to 157 in 1979. Yields are quite high by international standards, with 135 counties of the Plain recording grain yields of over six tons per hectare in 1979.

2. **Conjunctive Use in the North China Plain**

Surface water irrigation is well developed in the Plain, although the capture of run-off and its diversion relies to only a very limited extent on the silt-laden Yellow River. Significant surface storage exists in reservoirs damming rivers and their tributaries other than the Huang. In addition, there are tens of thousands of ponds for local storage,
virtually one per village, since they require little of external resources, have quick returns and can be built by local labor in periods of slack demand for agricultural labor inputs. A low weir across a river or stream (and possibly dredging upstream to deepen) can provide local storage and increase recharge of groundwater. Sometimes an ancient river course is used for local storage. In the basin of the Hai River, storage gates have been placed across some of the key drainage courses. In some areas of the Plain, farmers have developed networks of deep trenches, where the bottom of these trenches is 1 to 3 meters below the groundwater table depth in the dry season. A single commune can develop as much as 2 to 3 million cubic meters of storage in this fashion, enough to meet irrigation needs for 2 to 3 weeks. A medium sized trench has sufficient capacity to drain a one in ten year flood, and clearly the trenches also serve as sources of recharge to the shallow aquifer. Local depressions can be converted to shallow lakes, and this has been done in many areas, especially in the Plain of the Hai River. Yu and Wang estimate storage capacity in the Huang-Huai-Hai Plain at 3 billion cubic meters (BCM) for channel storage, 1.3 BCM for pond storage, and 1.7 BCM for lowland and shallow lake storage. Even allowing as much as 14 BCM for storage in large surface reservoirs and deep trenches, total estimated surface storage of 20 BCM is significantly less than the 48 BCM available in the fresh groundwater areas of the shallow aquifer. Thus, it comes as no surprise to learn that for the plain as a whole subsequent to the great tubewell boom of the 60s and 70s, the area irrigated by groundwater is more than twice that irrigated by surface water. Using the estimate of Huang (WEI) of 8 million hectares irrigated by tubewells, of which 1.3 million hectares are located on canal irrigation
systems, irrigated area per shallow well is 4 hectares and average pumpage per well per year is 3,375 cubic meters. Considering the usual decline in capacity due to clogging of filters, initially a shallow well may irrigate perhaps 6 hectares. Most of the wells are located on lands which do not have access to surface water supplies and the Chinese tend to plan water resource investments to rely one one or the other source. From this point of view, the hierarchical economic organization of agriculture in China (commune- brigade- team-family) facilitates choice of the most efficient delivery system as perceived at the local (i.e., commune) level. While the literature indicates a concern with efficient conjunctive use in a more global sense, it is not clear that the institutional basis for implementation of globally efficient use exists.

Huang (WEI) reports that the capital cost of a shallow well was about 5,000 yuan in 1982, and the income stream associated with such a well 1,500 to 2,000 yuan, with an indicated payout period of 3 to 4 years.41/ In order to encourage well investments during the 1973-81 period, a central and local government subsidy totaling 25 percent of investment cost was paid.

To organize the construction of millions of tubewells, development plans were prepared by provincial bureaus of water conservancy, and well drilling teams were set up by county water conservancy bureaus to assist farmers in well construction. Improved drilling technologies were introduced by the water conservancy technicians. A water jet drill developed by the Chinese is reported to have dug a 40 meter well within 24 hours.

41/ In 1984, one dollar exchanges for 2 yuan.
Huang also provides a review of some problems encountered in groundwater development, and these are quite similar to those reported elsewhere:

(1) Falling water tables, land subsidence, and wells going out of service.

(2) Deterioration of well capacity due to clogging of strainers and/or collapse of casing made of sandless concrete.

(3) Inefficient use of water and/or energy.

Huang estimates that approximately two-thirds of existing wells need renewal and advocates placing controls on the exploitation of the deeper aquifers of the Plain. He recommends that wells be drilled extensively adjacent to irrigation systems diverting Yellow River water—i.e., let the silt laden canals recharge the aquifer and draw a large proportion of irrigation water from imported canal supplies cycled through the aquifer.

Fei (WEI) reports increasing use of artificial recharge in China over the past ten years. The motives for injecting water have been to control land subsidence and for water storage. He estimates that as much as 10 BCM of surface water can be stored underground in the Plain for utilization in the dry season. Fei looks forward to the use of artificial recharge for controlling groundwater quality.

Jiang (WEI) reports increasing emphasis on efficient conjunctive use in lands irrigated from the lower reaches of the Yellow River. He notes that surface water is allocated to lands within close reach of a canal and the remaining lands are irrigated with groundwater. This strategy not only helps control the depth to water table but also assists in controlling the silt accumulations in canals and drains with Yellow
River supplies, which amounts to about 10 tons per irrigated hectare. Jiang cites calculations showing that diversions of Yellow River water for the People's Victory Canal can be reduced from 0.5 BCM to 0.14 BCM using a strategy of efficient conjunctive use, with a proportionate decrease in the volume of silt carried into the irrigation system.

In addition to controlling net recharge in the vicinity of a canal system (so as to prevent rises in watertable sufficient to create salination problems) and minimizing silt deposition problems (from Yellow River water), groundwater irrigation interacts with surface water irrigation in yet another way in the Huang-Huai-Hai Plain. In general, natural recharge in pure well irrigation areas is not sufficient to meet crop irrigation requirements, and the balance has to come from horizontal recharge from the upper canal system and artificial recharge with canal waste water. Cai (WEI) reports that of the pumpage of 9.1 million cubic meters in the Liuzhang-Xiazhuhuang pure well irrigation region in 1979, an estimated 6.5 million cubic meters, or over 70 percent, came from horizontal and artificial recharge.

Very clearly, Chinese irrigation engineers and farmers are making strong efforts to achieve efficient conjunctive use at the local level (i.e., individual canal command, county, commune) in the North China Plain. The fact that interbasin water transfer from the Chang Jiang (Yangtze) River system to the Huang-Huai-Hai Plain is projected for construction indicates efforts at globally efficient use as well. However, there is some evidence that the requisite institutional structures for implementation of efficient use on an interprovincial level are not yet in place. Nickum (WEI) reports that: (1) Chinese law provides little in the
way of guidelines for resolution of water disputes or water resource development. (ii) Divisiveness, rather than harmony, is the rule in interprovincial water disputes; and heretofore, interprovincial pacts have not necessarily been enforceable. (iii) The general consensus in China seems to be that the level of irrigation management is seriously inadequate. While points (i) and (ii) can only be resolved at the highest political level, China's leadership seems committed to reform when this will bring significant efficiency gains. With respect to the third point, Nickum's listing of the detailed complaints is a familiar litany to those acquainted with the current irrigation literature: 1) The irrigation bureaucracy emphasizes construction to the detriment of operations and maintenance which are both inefficient and inadequately funded. 2) Irrigation management personnel are short in supply and poorly trained. 3) Irrigation is emphasized to the neglect of drainage. 4) Secondary and Tertiary delivery systems are lacking or seriously delayed, and in consequence farmers sometimes open "indigenous cuts in the banks." 5) Those on the upper reaches use too much water, while those on the lower reaches do not receive enough. 6) Area served by each cubic meter per second of flow is too great. These all too familiar complaints raise once again the question of the information and skill requirements of irrigation systems, and the apparent difficulty of putting them in place in a developing country. On the other hand, the outstanding success of the province of Taiwan in this respect provides support for the expectation that the Chinese are capable of solving the problem.
It is difficult to interpret the Chinese experience in terms of the principles of quasi-legal allocation and the guidelines to efficient utilization since so much relevant information is not available and the institutional context is unique. It seems likely that the Chinese accept all of the principles of allocation, although only for the principle of source symmetry is the available evidence sufficient for a definitive conclusion. Of the three case histories examined, only China shows evidence of definite actions to achieve spatial efficiency. While a concern with intertemporal efficiency and resource sustainability can be assumed, evidence of specific actions directed toward these goals is lacking. With respect to institutional solutions to the problem of externalities in water resources, there seems to be no available evidence of attempts at global centralized control, trading in water rights or imposition of taxes/subsidies on pumping (or their quota equivalent). However, application of taxes and quotas levied at the commune level (and administered down to the team level) is a standard feature of Chinese economic policy. In addition, there is good evidence of efforts to achieve centralized control at the sub-regional level. Thus, both the tax/subsidy and centralized control remedies remain possibilities for China.

D. Review of Policy Responses to Externalities in Conjunctive Use

The case histories that have been reviewed show a wide diversity of policy responses. In order to put these responses in context, it is useful to compare them with respect to the quasi-legal allocation principles, efficiency guidelines and choice among institutional solutions to the problems of externalities discussed in Chapter two. This comparison is provided in Table 1. Note that a question mark following an answer in
Table 1 indicates that insufficient evidence is available to give a definitive answer. A yes and now answer indicates that each of the two answers is applicable to some sub-region.

Table 1: Conjunctive Use Policy Response Matrix

<table>
<thead>
<tr>
<th>Quasi-Legal Allocation:</th>
<th>California</th>
<th>China</th>
<th>Pakistan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Historical Water Rights</td>
<td>Yes</td>
<td>Yes?</td>
<td>Yes</td>
</tr>
<tr>
<td>Distributive Justice</td>
<td>Yes</td>
<td>Yes?</td>
<td>Yes</td>
</tr>
<tr>
<td>Loss Symmetry</td>
<td>Yes</td>
<td>Yes?</td>
<td>Yes</td>
</tr>
<tr>
<td>Source Symmetry</td>
<td>Yes and No</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Efficiency Guidelines:</th>
<th>California</th>
<th>China</th>
<th>Pakistan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial Efficiency</td>
<td>Yes and No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Temporal Efficiency</td>
<td>No</td>
<td>Yes and No?</td>
<td>No?</td>
</tr>
<tr>
<td>Resource Sustainability</td>
<td>Yes and No</td>
<td>Yes and No?</td>
<td>No</td>
</tr>
<tr>
<td>Spatial &amp; Temporal Efficiency</td>
<td>No</td>
<td>Yes and No?</td>
<td>No</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Choice of Institutional Solution:</th>
<th>California</th>
<th>China</th>
<th>Pakistan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fungible Legal Rights</td>
<td>No</td>
<td>No?</td>
<td>No</td>
</tr>
<tr>
<td>Efficiency Tax/Subsidy</td>
<td>Yes</td>
<td>No?</td>
<td>No</td>
</tr>
<tr>
<td>Centralized Control</td>
<td>Yes and No</td>
<td>Yes and No</td>
<td>No</td>
</tr>
<tr>
<td>Legal Local Control</td>
<td>Yes</td>
<td>Yes?</td>
<td>No</td>
</tr>
</tbody>
</table>

With respect to quasi-legal allocation principles, an affirmative answer (with some uncertainty) can be given for all cases on all principles except source symmetry. This was to be expected since the principles for which there is unanimity are essentially rules for maintaining the stability of the irrigation society. Source symmetry, which is essentially an allocation rule concerned with economic efficiency, shows a mixed picture with China a definite yes, Pakistan a definite no and California yes and no.
Answers with respect to the efficiency guidelines exhibit more ambiguity (i.e., yes and no answers) and more uncertainty. However, as with the responses to source symmetry, China shows more affirmative answers, Pakistan more negative answers, and California intermediate answers. A tentative (due to uncertainty) conclusion is that China has been more alert to the efficiency gains possible from conjunctive use than possibly California and certainly Pakistan.

With respect to a choice of institutional solution, neither China nor Pakistan have yet opted for solution that is both efficient and workable. California's choices are largely made and favor local control and pumping taxes. Given China's preference for local administration and the ease of administering taxes or quotas through the commune system, pumping taxes (or quotas) would seem to be a likely ultimate choice. Pakistan has effectively rejected the centralized control remedy and is confronted with a dilemma regarding the other alternatives. Neither a tax/subsidy nor a legal rights scheme is likely to be feasible until some form of water user association is in place along the country's 90,000 water courses.
IV. Some Analytical Methods for Managing Efficient Conjunctive Use

By now it should be clear to the reader that management of efficient conjunctive use is both complex and skill-intensive. In simple consequence, the potential for efficient management is constrained by the availability of skilled managers and technicians and the institutional restrictions which define the range of choices available to water management. From this perspective, the scope for immediately implementing a Pareto-efficient move toward more effective management is quite limited in many developing countries. However, over the longer run, skills can be acquired and institutional restrictions can be removed. Often, all that is needed is a convincing demonstration of the potential gains to be had. Once a strong, development-oriented leadership is convinced of the desirability of removing institutional and skill constraints, effective action usually follows. Where such a leadership is absent, effective and purposive action is unlikely in any event.

In the positive spirit that affirms the possibility of change once the feasibility of obtaining desired results from well-defined actions has been established, this section of the paper is devoted to a discussion of some recently developed analytical methods that facilitate the efficient management of conjunctive use. These methods all depend on developments from the parallel revolutions in mathematical modeling and digital computation of the past several decades. The ongoing development of ever less costly and more powerful computer hardware makes it certain that this technology will be extended ultimately to nations at all levels of development. The only real constraint to this diffusion is human skills and this is a removable constraint.
A. A Brief Review of Groundwater Modeling Methods

To set the stage for the following discussion, the comments of Gorelick (WEI) are reproduced:

"In the past two decades the field of groundwater hydrology has turned toward numerical simulations models to help evaluate groundwater resources. The application of finite difference and finite element methods to groundwater flow equations has permitted complex, real world systems to be modeled. Numerical simulation models have enabled hydrogeologists to develop a better understanding of the functioning of regional aquifers and to test hypotheses regarding the behavior of particular facets of groundwater systems. Models have become tools to evaluate the long-term impacts of sustained water withdrawals, groundwater-surface water interaction, and the migration of chemical contaminants.

Clearly, simulation as both a method to explore hydrogeologic problems and a tool to predict impacts upon groundwater systems will continue to be essential to hydrologists and to water managers. However, simulation models are often utilized to explore groundwater management alternatives. In such cases a model is executed repeatedly under various design scenarios which attempt to achieve a particular objective, such as isolating a plume of contaminated groundwater, preventing saltwater intrusion, dewatering an excavation area, or obtaining a sustainable water supply. Use of such an approach often sidesteps rigorous formulation of groundwater management goals and fails to consider important physical and operational restrictions. Determining the proper objective function in a groundwater management model is often difficult but is an essential aspect of management modeling and should not be avoided. It is unlikely that optimal management alternatives will be discovered using simulation techniques alone. What is required is not a simulation model alone, but a combined simulation and management model. Recently, joint simulation and management models have been developed. A combined model considers the particular behavior of a given groundwater system and determines the best operating policy under the objectives and restrictions dictated by the water manager."

42/ Gorelick (WEI), pg. 305.
Following Gorelick, studies which link aquifer simulation with management decision models are classified into two major classes: (i) hydraulic management models, and (ii) policy evaluation and allocation models, as in Figure 1. Models aimed primarily at managing groundwater stresses such as pumping and recharge are included in the first class. These models treat the stresses and hydraulic heads directly as management decision variables. Models which simulate the behavior of economic agents, where the environment includes complex groundwater-surface water interactions and specific institutional content are included in the second class. Although these models are not explicit policy selection models, they can be used to evaluate policy alternatives. More complex multilevel optimization models linked to agent simulation submodels do generate specific optimal allocation policies. Both classes of model utilize linear or quadratic programming methods. In both classes of model, the component simulating aquifer response is based on the equation of groundwater flow in saturated media (Pinder and Bredehoeft, 1968; Remson, et. al., 1971).

1. Groundwater Hydraulic Management Models

These models incorporate a simulation model of a particular groundwater system as constraints in a management decision model. "In the embedding method, finite difference or finite element approximations of the governing groundwater flow equations are treated as part of the constraint set of a linear program. Decision variables are hydraulic heads at each node as well as local stresses such as pumping rates and boundary conditions. In the response matrix approach an external groundwater simulation model is used to develop unit responses. Each unit response describes the influence of a pulse stimulus (such as pumping for a brief period) upon
Figure 1: Classification of Groundwater Management Models

GROUNDWATER MANAGEMENT MODELS

Groundwater Hydraulic Management Models
  - Embedding Method
  - Response Matrix Approach

Groundwater Policy Evaluation and Allocation Models
  - Hydraulic Economic Response Models
  - Linked Simulation-Optimization Models
  - Hierarchical Models

hydraulic heads at points of interest throughout a system. An assemblage of the unit responses, a response matrix, is included in the management model. The decision variables in a linear, mixed integer, or quadratic program include the local stresses such as pumping or injection rates and may include hydraulic heads at the discretion of the modeler."

2. Groundwater Policy Evaluation and Allocation Models

These models analyze water allocation and investment problems from the viewpoint of economic efficiency. As Figure 1 indicates, there are three types of these models: (i) hydraulic-economic response models extend the response matrix approach to include agricultural supply response and/or surface water allocation. They are formulated as single optimization problems in which both hydraulic and economic target and instrument variables are included. (ii) Linked simulation-optimization models use the output from an external aquifer simulation models as an input to an economic optimization model(s). The linked model allows more economic and institutional content in the decision model, while the hydraulic non-linearities are treated separately to avoid the need for either linearization or non-linear programming. These models are concerned with economic objectives and have been used to evaluate alternative policies (e.g., quotas and taxes on pumping). (iii) Hierarchical or multilevel models consider multiple optimizing agents in a hierarchical decision structure. In the simplest possible case, this would be the government (considered as monolithic) and farmers (considered collectively in terms of a representative farmer). Typically, they involve some type of area decomposition, although this is not always necessary. The aquifer model tends to be simplified, e.g., a two-dimensional asymmetric, polygonal

finite difference system, since only broad, area wide hydraulic variables are considered. Large and complex systems can be decomposed into subsystems and decomposition methods used in solution. However, if objectives differ between groups of agents, the resulting problem will be non-convex, and only local optima may be obtained. Thus, some structural simplification is necessary if such problems are to yield reliable, policy relevant results.44/

B. Finding an Acceptable Policy

Although it is neglected in the literature, all analysts who use modeling methods are familiar with the extended dialogue between modeler and policy maker that is intrinsic to any direct application of results from simulation experiments. Quite often in such a dialogue, critical political trade-offs will only emerge when a policymaker is confronted with recommendations (derived from model experimentation) that he suddenly finds unacceptable. At such junctures, it is useful to explore alternative policies that involve less agonizing political trade-offs. Rogers, Harrington and Fiering (WEI) point out that programming models quite often generate flat response surfaces for which alternative feasible solutions differ little from the optimal solution with respect to the value of the criterion function (e.g., agricultural income) but represent quite different values for key decision variables. When the simulation model generates such a flat response surface, a solution which differs from the optimal solution by say only one percent of the value of the criterion function may specify decisions which are much more acceptable politically—e.g., changing the sequence of construction for several reservoirs may

44/ See Bisschop et. al. for a discussion of this problem.
enable a policymaker to initiate construction in a politically sensitive region at quite low real cost.

Rogers, Harrington and Fiering note that it is useful to identify those decisions which would remain nearly intact under a variety of goals and conditions, a property that is known as system resilience. Variables, i.e., decisions, which remain in the solution at about the same level for many feasible solutions in the neighborhood of the optimum are said to be tight, in contrast to diffuse variables which take widely differing values. A sensible negotiating strategy would be to fight to retain tight variables, while giving ground with respect to diffuse variables. In this fashion, controversies can be minimized and a consensual solution becomes easier to obtain.

C. An Application of Multilevel Policy Evaluation and Allocation Modeling

The modeling of the Indus Basin Irrigation System of Pakistan by O'Mara and Duloy (WEI) is perhaps the earliest application of modeling methods to an analysis of efficient conjunctive use for a large alluvial basin that preserves enough of the structural characteristics of the system modeled to provide direct answers to practical policy questions. The background information on the development of conjunctive use in Pakistan has already been discussed in considerable detail in Section III. B. As that discussion showed, in Pakistan at present, the government through provincial irrigation departments controls the annual allocation of some 100 million acre-feet (MAF) of surface water diverted through the largest integrated irrigation system in the world. On the other hand, 75 percent of some 30 MAF of annual tubewell withdrawals is controlled by hundreds of thousands of individual farmers with private tubewells. Given an estimated
overall canal system efficiency of 40 percent, it is clear that canal seepage losses are a major source of recharge to what is essentially one single unconfined aquifer, albeit one with substantial local variations in water quality. The very difficult problem of coordinating the tubewell pumping of large numbers of farmers with the canal water diversions of the government so as to achieve efficient overall resource use has thus far eluded the grasp of policymakers and administrators in Pakistan. The Indus Basin Model was designed as an analytical instrument for broad policy evaluation purposes; but most particularly, to help address the very difficult coordination and control problem of efficient conjunctive use in the Indus Basin.

Models designed for policy analysis normally involve two kinds of agents: policy makers and policy receivers. If the policy receivers are optimizing agents, one is faced with a hierarchical or multilevel decision-making problem. In the case of the Indus Basin Models, the government plays the role of the policy maker, while the farmers play the role of the policy receivers. The government decides on water-related investments and surface water allocations, and sets (some) agricultural prices, taxes and/or subsidies. The farmers, in turn, react to the setting of these policy instruments by using water (both surface and ground water) and other inputs, making private investments in tractors, tubewells, etc., and choosing cropping patterns so as to maximize their own welfare. Generally speaking, an efficient strategy is to separate analytically the two types of decision-makers by simulating the response of the policy receivers to the actions of the policy makers in the model per se and to represent the actions of the policy makers by changes in model structure.
and/or parameters. However, there are exceptions to this rule, particularly in the instance of policy constraints due to physical externalities (e.g., surface-ground water interactions) that are not recognized by policy receivers.

The basic structure of the Indus Basin Model can be visualized as follows. The entire basin is partitioned into 53 irrigated regions, referred to as polygons. Each polygon is essentially homogeneous with respect to ground water, and preserves boundaries that are significant to the groundwater aquifer system. Linkages in water supply that arise from seepage of surface water to the aquifer and withdrawal of ground water via tubewells or capillary action as well as underflows between polygons are explicitly modeled for each polygon, thereby interlocking the polygons. Each polygon also receives surface water on a monthly basis from one or more control points of the surface water delivery system.

In order to embed those differences in soils, climate, etc., that create regional comparative advantage in different crops, model cropping technologies were specialized to nine agro-climatic zones (ACZs). The surface water distribution system was superimposed on the complex mapping of groundwater areas (i.e., polygons), canal commands and ACZs by means of a network formulation.

Each polygonal model has embedded in it a single farm level model to characterize the agricultural production system of the area. Such a farm level model simulates the resource allocation choices of a single representative farmer which determine the production of disposition of 11 crops and 4 livestock commodities. Exogenous resource limitations are imposed on land, labor and canal water. The water supply and demand
constraint of each farm level model includes estimates of water available from rainfall, evapotranspiration from the aquifer, the exogenous supply of canal and government tubewell water, and the endogenous supply of private tubewell water. However, when used to evaluate water allocation policies, canal water allocations are endogenous. There is, of course, great uncertainty associated with the availability of surface water, and estimates are based on long-term averages and worst cases. The uncertainty associated with the amount of rainfall is not so important as its contribution to the overall water supply is quite small.

In the water constraint, the endogenous sources of water for cropping are only private and tubewell and canal water. This is due to a treatment of rainfall and sub-irrigation which nets them out on a per acre basis from the crop water requirement coefficients. This approach makes crop use of rainfall and sub-irrigation endogenous since an acre of land must be cropped in a given month if these supplies are to be available for use. All polygonal models have a groundwater balance constraint, which may be deleted in certain solutions. Briefly put, this constraint forces equality between additions to and withdrawals from the aquifer. The presence of this constraint is crucial to the solutions of the basinwide model with endogenous canal water allocation. Without it, the solution is not an equilibrium in the sense that it would be indefinitely sustainable.

The original Indus Basin Model was a linear programming problem with more than 20,000 constraints, with an objective function for the basinwide model that is simply the sum of the objective functions of the polygonal sub-models. A model of this size exceeds the capability of existing software for linear programs. By converting the height of the
water table in each polygon to a policy instrument, structural simplifications could be made such that the entire model contains less than 8,000 constraints, which is solvable using a large machine and commercial software.

As individual farmers do not recognize their individual effects on ground water equilibrium which must be maintained over the long run, the government must take into account the long-term consequences of any water allocation scheme and the impact of water related investments on equilibrium. This expresses precisely the two-level aspect of the Indus Basin Model where some constraints are not formally recognized by the farmers (the policy receivers) even though the government (the policy maker) requires that they be satisfied. How the government might accomplish this task is explained in detail in Bisschop et. al. (1982). Briefly stated, the main result is that if groundwater balance is imposed, the dual variable (i.e., shadow price) corresponding to this constraint is the tax or subsidy which would induce farmers to pump tubewells at the level required for groundwater balance.

In order to evaluate existing and potential water allocation policies for the basin, a sequence of simulation experiments were performed. Each experiment tested the steady state response of agricultural production and employment to a different policy rule for water allocation. In each case (save one), the groundwater balance constraint was included for each polygon, and the value of the dual variable (i.e., accounting or shadow price) in the solution indicated the tax or subsidy on tubewell pumping required to induce farmers to pump at the desired levels. In addition, endogenous drainage investment variables were included for the
saline groundwater areas in order to test the efficiency of increased water allocations (and associated drainage) for these areas.

Results from these experiments showed overall gains ranging from 17 to 20 percent above base level for agricultural production (i.e., value added) and from 14 to 16 percent for agricultural employment. However, when decomposed between fresh groundwater (FGW) and saline groundwater (SGW) areas, the results show the former increasing only 2 to 4 percent for both measures, while the latter showed gains of 55 to 65 percent in production and from 45 to 54 percent in employment. That is, the several alternative allocation rules showed little differences among themselves, but indicated significant gains were possible in comparison with existing policy. The reasons for the striking difference in the output and employment responses of FGW and SGW areas become clearer when the solution results with respect to land and labor intensity are analyzed. The base level data show divergent levels of input intensity for both inputs between FGW and SGW areas, with higher intensities prevailing in the FGW areas. At the level of the entire basin, the effect of alternative system management policies is to bring the levels of input intensity much closer to equality between the two groundwater quality regions.

Note that the gains indicated by the simulation experiments were estimated holding everything else constant and under conservative assumptions with respect to water supply. However, these gains require optimally coordinated use of surface and ground waters. Necessary steps to achieve the potential gains from more efficient conjunctive use are: (i) enabling investments in drainage works in saline groundwater areas, and (ii) public control of private tubewell withdrawals in the fresh
groundwater areas by means of some combination of taxes, subsidies, quotas, fees, prices, etc. These steps can be regarded as adjustment costs in a transition toward more efficient resource utilization. Of the two steps, enabling investments in drainage works in SGW areas are clearly first priority since a reallocation of surface waters in which relatively more goes in the SGW areas is not feasible without the drainage investments in place. Policy control over private tubewell pumping will not be necessary for many years. In effect, the experiments are saying that previous neglect of drainage investments has created a situation where the payoffs from such investments can be quite high.

D. Measurement of the Costs Due to an Externality

The externality between farmers that is induced by dependence upon a common aquifer or stream-aquifer system for water supply is susceptible to measurement, and any of the policy remedies proposed for removing the inefficiency and/or inequity due to an externality depend upon the feasibility of measurement. In practice, the complexity of the physical systems usually precludes the derivation of an analytic solution that can serve as a guide to policy in a variety of cases. Thus, the measurement of the externality in any given aquifer or stream-aquifer system is usually accomplished by constructing a numerical simulation model that characterizes the particular system under study. An example of this approach is the modeling of the Indus Basin of Pakistan described by O'Mara and Duloy (WEI). While this approach is both straightforward and flexible in that it permits simulation of the effects of a number of policy remedies, it remains skill, data and time intensive. For this reason, its application tends to be limited to situations where potential benefits justify the costs.
Another approach to the measurement of the cost of an externality in an aquifer or stream-aquifer system has been developed by Zapata (WEI). This approach uses econometric methods and has the virtue that it is less skill, data and time intensive than a numerical simulation model if the time series data it requires are available. It has the disadvantage that simulation of the effects of alternative policy remedies is not feasible. However, where an estimate of the difference between social and private costs can be used to determine a key policy parameter, e.g., the optimal tax on pumping, then the method of Zapata can be used to advantage.

In an empirical application of his method to two regions of Mendoza Province, Argentina, Zapata found the difference between social and private costs to be 20 percent of private costs in one region and 30 percent in the other.
V. Some Analytical Results with Respect to Efficient Conjunctive Use

A. Dynamic Conjunctive Use to Minimize Income Fluctuations

One of the most attractive benefits from efficient conjunctive use of surface and ground waters is the possibility of using the groundwater aquifer as a massive underground reservoir, which is managed so as to minimize fluctuations in total water supply due to random variation in ambient rainfall and rim station inflows (for well defined alluvial basins). Efficient dynamic conjunctive use programs increased groundwater withdrawals to offset diminished surface supplies in times of drought, permitting temporary mining of the aquifer, and programs greater than normal surface water application (and diminished groundwater pumping) to replenish aquifer supplies in times of heavy surface supplies. With a stabilized annual water supply agricultural production and incomes are also stabilized. Of course, efficient dynamic conjunctive use requires sufficient capacity in both surface delivery and tubewell pumping to meet peak requirements in an efficient dynamic program. If the surface water delivery system and tubewell pumping are controlled by different agencies, a potential problem of coordination exists in both aquifer management and investment planning for surface water delivery and tubewell pumping capacity. In practice, as already noted in Chapter III, these two sources of water supply are usually managed by separate agencies. The outcome is usually inefficient conjunctive use; and often there is over-investment by one agency in order to achieve those dynamic efficiencies which can be obtained in the absence of coordination.
In a study of efficient intertemporal use of surface and ground waters in the South Platte Valley of the US state of Colorado, Bredehoeft and Young (WEI) found that actual installed well capacity was approximately sufficient to irrigate the entire area, which would appear to be an over-investment in well capacity. Using a simulation model which coupled the hydrology of a conjunctive stream-aquifer system to an economic model simulating farmer production and investment decisions, they investigated the pattern of conjunctive use in an environment where surface flows are allocated by a system of historic water rights (e.g., "first in time, first in right"), and tubewell investments and pumping are controlled by individual farmers. The results of Bredehoeft and Young suggest that given the existing institutional arrangements with respect to allocation of surface and ground water and prevailing prices and technology, optimal groundwater pumping capacity for an individual farmer should be capable of irrigating his entire acreage. Installing this level of capacity not only maximized expected net benefit, it also reduced the variance in annual income to essentially zero. Of course, heavy pumping by upstream users can reduce the return flow available to downstream users from surface supplies; and this problem has given rise to litigation in Colorado. Thus, the optimal investment response by individual farmers upstream, given prevailing institutional arrangements, imposes an externality on users downstream. In short, what is optimal for one group of agents in an institutional context where there is a failure in overall coordination, may impose losses on others. In the Colorado case, adjudication forced the upstream tubewell pumpers to tax themselves to secure additional supplies to make good the losses to downstream users.

In some arid regions, the only available natural source of water is groundwater; and if external developments induce rapid population and economic growth, the pressure on the resource may threaten its continued productivity. Thomas (WEI) reports on two case studies of countries in arid regions, Qatar and Libya, where discovery and development of petroleum resources has resulted in rapid population and income growth. In both cases, the resultant increase in demand for water had led to exploitation of aquifer systems beyond the safe yield and the predictable consequence of sea water intrusion. Advisers from FAO have participated in planning efforts exploring the policy options for dealing with the situation, and Thomas' paper briefly describes the results from simulation experiments that model the policy options. Since both governments place a priority on an extreme form of food security, full self-sufficiency, the policy options range from total reliance on food imports to total reliance on domestic production. In both cases, Thomas finds that a policy of utilizing the local aquifer at the safe yield level and relying on food imports for the remainder of supply is the least cost policy. At the other extreme, nearly full self-sufficiency is approximately ten times as costly in both cases. The large increase in costs arises in both cases from the necessity of either desalinizing sea water or importing fresh water from a great distance in order to achieve the requisite levels of agricultural production. Since both countries have sufficient income from petroleum production to consider the full range of options, the choice of the policy makers (which Thomas does not report) clearly depends on the value weights attached to such policy objectives as full food self-sufficiency. However,
as in the case of California, policymakers apparently have deferred taking positive action on a water resource problem due to an externality until the consequences of further delay would be very costly.

C. Case Study of Planning for Conjunctive Use

Basu and Ljung (WEI) analyzed a traditional surface irrigation system in India for which actual performance of 15 years had deviated significantly from project design objectives. For this case, total canal system efficiency was only 20 percent; and this low efficiency was largely responsible for the poor project performance. However, the area was underlain by both shallow and deep aquifers; and the increase in recharge due to the leaky canal system had induced a secular rise in the water table (for the shallow aquifer) of 0.14 meters per year. With a depth to water table of 6 to 16 meters, a number of farmers had installed shallow tubewells; and an estimated 44 million cubic meters (MCM) were pumped annually, about 30 percent of estimated gross additions to aquifer storage. With median canal head releases of 230 MCM yielding only an estimated 46 MCM at the root zone, it was evident that water utilization was significantly conjunctive. The issues were the efficiency and equity of the existing arrangement. Basu and Ljung estimated on the basis of preliminary hydrological balances that an additional 50 MCM of groundwater could be extracted within the safe yield of the shallow and deep aquifers. They projected the exploitation of the deep aquifer from a battery of deep public tubewells, whose discharge would be to the existing canals; while instituting a program of incentives to encourage farmers to exploit the shallow aquifer.
Another important achievement of the planning exercise was the development of a model which consists of five interrelated modules: (i) rainfall infiltration and run-off, (ii) soil moisture balance, (iii) evapotranspiration and moisture up-take by the crop, (iv) irrigation schedule, and (v) yield response to moisture stress. The model deals entirely with physical phenomena relating crop performance of time-dated water supplies, but the output can be fed into economic models of farmer behavior. The model was calibrated for several watercourse commands at the head and tail reaches of a distributory (i.e., tertiary) canal of the system. With this analytical instrument, the response of crops to varying numbers of irrigations and quantities of water per irrigation from both canal and ground water supplies was studied (on the assumptions of fixed cropping patterns and a static depth to water table). Using the model, they worked out feasible canal schedules of a fixed rotation type, and then generated groundwater pumping schedules which maximized yields of major crops, given system constraints. In this way, they were able to show that significant gains were possible from more efficient conjunctive use.

However, they have not, as yet, linked their physical response model to a model of the economic behavior of farmers; and, for this reason, issues concerning policies to achieve efficient coordination of the actions of public officials with respect to canal releases and farmers with respect to private tubewell pumping have not been resolved. An economic model of the kind described by O'Mara and Duloy (WEI) can resolve this issue by simultaneously solving for the optimal schedules of conjunctive use and the tax or subsidy on private tubewell pumping that will induce farmers to pump
at optimal levels. Thus, the tools exist for an extension of the work described by Basu and Ljung to economic modeling that assesses the effect of alternative public policies to achieve efficient conjunctive use.
VI. **Summary**

Quite clearly the difficulties in achieving efficient conjunctive use of ground and surface water discussed in this paper are problems of middle aged irrigation systems in alluvial basins. However, such difficulties will eventually surface in over half of the irrigated areas of the world. Moreover, they are already painfully evident in three great alluvial basins - the Indus and Gangetic Plains of South Asia and the North China Plain - that are dominant in the irrigated agriculture of three nations accounting for close to half of the world's population. Thus, the issue of efficient conjunctive use is important to the welfare of a majority of the population of the developing countries of the Third World.

The difficulty is due on the one hand to physical interdependence between surface water distribution and the groundwater aquifer; and on the other, to the need to coordinate the activities of two sets of agents - individual farmers (or production teams in China) controlling tubewell pumping and surface water irrigation system managers controlling canal diversions. The concept prevalent in the 1960s that the government could easily coordinate pumping and canal diversions by keeping control of both in state hands has been superceded by the reality of farmer control of pumping in the major alluvial basins reviewed. In fact, the evidence from the Pakistani experience suggests that even when the government starts with control of both sources in state hands, the management problem has been too difficult for existing irrigation bureaucracies to resolve satisfactorily. In short, the focus has shifted from blind faith in a benevolent, omnipotent state to skeptical scrutiny of all too fallible and short-sighted irrigation system managers.
In point of fact, the top down philosophy of the planners has always been conceptually as well as practically flawed because it did not take into account either the objectives and preferences of the farmers nor the particular moral hazards to which irrigation managers are exposed. It is now apparent that a feasible conjunctive use plan must recognize not only farmer insistence on only pareto-safe policy changes but also the farmer objective of some control over the water allocation process. An allocation policy which provides for at least limited farmer participation in the process is also very likely to diminish the exposure of irrigation managers to moral hazard. Since farmer participation will inevitably require cooperation among farmers, the need for development of water users associations becomes a first order priority. This is not a field in which the Bank can presently claim any expertise, and a program of research on cooperative use of water could prove highly productive in terms of improved understanding and more effective irrigation projects.

Along with better understanding of cooperation among water users, there is a need for better understanding of irrigation management. Improvement in irrigation operations has long been neglected in a search for technical (i.e., design and investment) solutions. Since an irrigation system may have a service life of a century with only relatively minor changes in structure, it is perhaps not surprising to find areas where irrigation management has been technically static for decades. Yet, as the experience of Taiwan shows, significant improvement in performance is possible by designing operations around the constraints of older structures. Given that efficient conjunctive use is information and skill intensive, large improvements will be necessary in both the skills of
irrigation managers and the quality of the management information and
control systems at their disposal.

The review of ongoing experience in conjunctive use for several
major irrigated regions has yielded several propositions that may serve as
working hypotheses until further experience either provides additional
confirmation or serves to reject them. For example, the California
experience suggests farmers will act to cope with external diseconomies
only when they are actually confronting serious adverse consequences. In
this respect, Pakistani experience confirms since farmers in FGW areas both
accept the status quo and have yet to suffer significant losses from
externalities. On the other hand, farmers in many SGW areas have suffered
significant losses from waterlogging and salinity; and their
dissatisfaction has fueled a demand for drainage investments.

Another clear, if obvious, proposition is that farmers (and
bureaucrats) will only seek a remedy when they believe a remedy exists.
This proposition has one clear and important implication: neither farmers
nor bureaucrats will accept proposed solutions whose mode of action is
beyond their understanding if not their experience. For this reason,
irrigation professionals have a responsibility to communicate in simple
language to all the concerned parties those technical results which can be
used to significantly improve irrigation efficiency if the implementation
of these results requires action by those concerned. A somewhat negative
confirmation of this proposition comes from the Chinese experience in the
North China Plain, which is dominated by the problems presented by the
heavy load of silt that the Huang (i.e., Yellow) River picks up in the
loess plateau region of China. Both the design of canals and the location
of tubewell fields in the area of the Huang in the North China Plain are heavily influenced by the need to cope with the enormous mass of silt that the Huang carries. However, there are no large scale efforts to control erosion in the loess plateau region. Apparently this action is not believed to be a feasible solution to the problem.

Finally, some perspective on the recent advances in analysis and simulation of complex, conjunctive use regimes is in order. The mathematical modeling and computer methods required for the more sophisticated conjunctive use schemes are now being rapidly diffused. They are now in the engineering curricula of universities around the world. However, while one can read of courses in these methods at regional universities in India, at present it is difficult to find them being applied in India. That will change as a new generation of graduates replaces an older generation accustomed to different methods. The real problem is not analytical methods, nor is it a shortage of people with relevant skills. The real problem is skepticism with respect to prospective gains combined with a glacial resistance to institutional change due to the belief that changing the status quo is not pareto-safe on the part of at least some participants capable of blocking change.
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APPENDIX A

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Bredehoeft, J.D. and R.A. Young, "Conjunctive Use of Ground Water and Surface Water for Irrigated Agriculture: Risk Aversion".

Coe, J.J., "Responses to Some of the Adverse External Effects of Ground Water Withdrawals in California."

Fei, J., "Explanation of the Hydrogeologic Map of Storing Surface Water Underground in the Huang-Huai-Hai Plain".


Huang, R., "Development of Ground Water for Agriculture in Lower Yellow River Alluvial Basin".

Jiang, P., "A Concept of Conjunctive Use of Surface and Ground Waters in Lower Reaches of Yellow River".

Johnson, S.H. III, "Large-Scale Irrigation and Drainage Schemes in Pakistan: A Study of Rigidities in Public Decision Making".

Nickum, J.E., "Institutions and China's Long-Distance Water Transfer Proposals".


Radosevich, G.E., "Legal Considerations and Alternatives for Organizing Water Users".

Randall, A., "The Problem of Market Failure".

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Thomas, R.G., "Groundwater as a Constraint for Irrigation".

Zapata, J.A., "The Estimation of Externalities of Groundwater Use in the West of Argentina".
APPENDIX B

WORKSHOP PARTICIPANTS

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### A Glossary of Some Technical Terms Relating to the Management of Steam-Aquifer Systems

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>groundwater table</td>
<td>the level of water storage (above mean sea level) in an aquifer, i.e., point at which soil is fully saturated with water.</td>
</tr>
<tr>
<td>underflows</td>
<td>underground flow or movement of water in an aquifer.</td>
</tr>
<tr>
<td>recharge</td>
<td>change (per unit of time) in water stored in an aquifer, which may be negative. It is defined by the identity: recharge = additions - withdrawals + net underflows</td>
</tr>
<tr>
<td>mining of aquifer</td>
<td>persistent withdrawals in excess of mean recharge</td>
</tr>
<tr>
<td>secular reserves</td>
<td>volume of groundwater capable of being mined.</td>
</tr>
<tr>
<td>long term storage capacity</td>
<td>total capacity of the aquifer to store water.</td>
</tr>
<tr>
<td>underground transmission</td>
<td>water distribution by means of underflows within an aquifer system.</td>
</tr>
<tr>
<td>evapotranspirative withdrawals</td>
<td>boundary effect occurring when the watertable is near the surface which induces withdrawals of water due to capillary action and plant suction.</td>
</tr>
<tr>
<td>waterlogging and salinization</td>
<td>unproductive soil condition which occurs when watertable is very near the surface.</td>
</tr>
<tr>
<td>energy cost of pumping</td>
<td>cost of the energy required to efficiently pump a unit of water from the aquifer.</td>
</tr>
<tr>
<td>groundwater quality</td>
<td>defined by the level of dissolved salts or other contaminants. Quality also depends on the intended use.</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
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<tr>
<td>rim station</td>
<td>-- a flow measurement point at which a river carrying runoff from the mountain enters the plains of an alluvial basin.</td>
</tr>
<tr>
<td>mean long-term recharge</td>
<td>-- is an average annual recharge, exclusive of net pumping, where the average is taken over enough years to obtain a tight confidence interval on the estimate of population mean.</td>
</tr>
<tr>
<td>stochastic steady state</td>
<td>-- an equilibrium that exists only in terms of the long run average and periodic observations will differ from the long run average due to random (i.e., stochastic) variation.</td>
</tr>
<tr>
<td>hydraulic head</td>
<td>-- force vector due gravitation on a liquid body.</td>
</tr>
</tbody>
</table>
World Bank Publications of Related Interest

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Gershon Feder, Richard Just, and David Silberman

Agrarian Reform as Unfinished Business—the Selected Papers of Wolf Ladejinsky
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Explains the complex relationships in training and visit extension and draws attention to the range of considerations that are important to implementing the system.
1984. 95 pages.

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Points out that developing countries must invest more in agricultural research if they are to meet the needs of their growing populations. Notes that studies in Brazil, India, Japan, Mexico, and the United States show that agricultural research yields a rate of return that is more than two to three times greater than returns from most alternative investments and cites some of the successes of the high-yielding varieties of rice and wheat that were developed in the mid-1960s. Discusses the World Bank's plans to expand its lending for agricultural research and extension, particularly for the production of food and other commodities that are of importance to low-income consumers, small farmers, and resource poor areas.


Stock Nos. BK 9074 (English), BK 0160 (French), BK 0161 (Spanish). $5 paperback.

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Argentina: Country Case Study of Agricultural Prices, Taxes, and Subsidies
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The Johns Hopkins University Press. 1983. 624 pages (including maps, bibliographies, index).


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Sets out a careful and practical methodology for analyzing agricultural development projects and for using these analyses to compare proposed investments. It covers what constitutes a “project,” what must be considered to identify possible agricultural projects, the life cycle of a project, the strengths and pitfalls of project analysis, and the calculations required to obtain financial and economic project accounts.
The methodology reflects the best of contemporary practice in government agencies and international development institutions concerned with investing in agriculture and is accessible to a broad readership of agricultural planners, engineers, and analysts. This revision adds a wealth of recent project data; expanded treatment of farm budgets and the efficiency prices to be used to calculate the effects of an investment on national income; a glossary of technical terms; expanded appendixes on preparing an agricultural project report and using discounting tables; and an expanded, completely annotated bibliography.
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Managing Information for Rural Development: Lessons from Eastern Africa
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Monitoring Rural Development in East Asia
Guido Deboeck and Ronald Ng

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Guido Deboeck and Bill Kinsey

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Guido Deboeck and Bill Kinsey

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Guido Deboeck and Bill Kinsey
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The Johns Hopkins University Press. 1982. 336 pages (including maps and index).

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Describes the successes and failures of China's rural development policy. Helps clarify both the strength and weaknesses of a self-reliant strategy of rural development.

Rural Financial Markets in Developing Countries
J. D. Von Pischke, Dale W. Adams, and Gordon Donald
Selected readings highlight facets of rural financial markets often neglected in discussions of agricultural credit in developing countries. Considers the performance of rural financial markets and ways to improve the quality and range of financial services for low-income farmers. Also reflects new thinking on the design, administration, evaluation, and policy framework of rural finance and credit programs in developing countries.

Rural Poverty Unperceived: Problems and Remedies
Robert Chambers
Staff Working Paper No. 400. 1980. 51 pages (including references).
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Rural Projects through Urban Eyes: An Interpretation of the World Bank's New-Style Rural Development Projects
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