World Bank Reprint Series: Number 334

REP-0334

Gerald T. O'Mara and John H. Duloy

NOV, 1984

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WATER RESOURCES RESEARCH, VOL. 20, NO. 11, PAGES 1489–1498, NOVEMBER 1984

Modeling Efficient Water Allocation in a Conjunctive Use Regime: The Indus Basin of Pakistan

GERALD T. O'MARA AND JOHN H. DULOY

Agricultural and Rural Development Department, The World Bank, Washington, D. C.

Efficient resource use where ground- and surface waters are used conjunctively may require special policies to rationalize the interaction between water use by farmers and the response of the stream aquifer system. In this paper, we examine alternative policies for achieving more efficient conjunctive use in the Indus Basin of Pakistan. Using a simulation model which links the hydrology of a conjunctive stream aquifer system to an economic model of agricultural production for each of 53 regions of the basin together with a network model of the flows in river reaches, link canals, and irrigation canals, we have studied the joint effect of various canal water allocation and associated private tube well tax or subsidy policies on overall system efficiency. The results suggest that large gains in agricultural production and employment are possible, given more efficient policies.

1. INTRODUCTION

The objective of this paper is to present some simulation results on a efficient conjunctive use for the irrigated agriculture of the Indus Basin of Pakistan. The Indus Basin has been the subject of a number of studies in the past several decades, as the long run effects of the introduction of large-scale canal irrigation to the flat, slowly draining Indus plains, i.e., waterlogging and salinization, became increasingly troublesome [e.g., *Chaudry et al.*, 1974; *Fiering*, 1965; *Greenman et al.*, 1967; *Irrigation and Agricultural Consultants Association* (*IACA*), 1966; *Lieftinck et al.*, 1968; *Revelle*, 1964; *Tipton and Kalmbach Inc.*, 1967; *Water and Power Development Authority* (*WAPDA*)–*Harza Engineering Co.*, 1963; *WAPDA*, 1979]. The studies of WAPDA-Harza, Revelle, IACA, Tipton and Kalmbach, and Lieftinck et al. were unanimous in recommending large-scale public tube well development for vertical drainage and to achieve efficient conjunctive use, although the long-term need for horizontal drainage to remove salt accumulations was recognized. These recommendations were incorporated in the government's investment program of the 1960's and 1970's. In retrospect, these studies underestimated both the strength of the incentives for private tube well investment and the difficulties in implementing and managing a massive public tube well operation. These difficulties and the Pakistani response have been carefully documented by *Johnson* [1982]. At present, about three quarters of tube well withdrawals are by private agents, and the problem of achieving efficient conjunctive use has been completely transformed from that envisioned by the scenarios of the 1960's [*WAPDA*, 1979].

The problem of efficient conjunctive use is inherently dynamic, and much of the early work was explicitly dynamic [e.g., *Buras*, 1963; *Burt*, 1964, 1966, 1967; *Bredehoeft and Young*, 1970; *Brown and Deacon*, 1972; *Noel et al.*, 1980]. However, dynamic optimization suffers from the curse of dimensionality, and necessarily dynamic models must simplify to the point that significant aspects of real world applications must be suppressed. This dilemma has led to modeling methods that are not explicitly dynamic, e.g., static "steady state" models, such as that of *Rogers and Smith* [1970]. Excellent reviews of the state of the art in modeling groundwater and stream-aquifer systems are found in the work of *Bachmat et al.* [1980] and *Gorelick* [1983]. Modeling that incorporates more real world detail has uncovered potential conflicts between public and private interests stemming from the physical linkage between operations by individual well operators created by reliance on a common aquifer, i.e., a physical external diseconomy or simply externality. This has led to a characterization of the problem as a hierarchial or multilevel one [*Yu and Haimes*, 1974]. One device for closing the gap between public and private interests caused by the externality is some form of tax and/or quota on pumping, and this solution has been explored in a number of studies [e.g., *Bredehoeft and Young*, 1970; *Maddock and Haimes*, 1975; *Feinerman and Knapp*, 1983]. The present study utilizes a static deterministic formulation, multilevel structure, and a tax/subsidy instrument in analyzing efficient conjunctive use.

Paper number 4W1019.
0043-1397/84/004W-1019$05.00

This study had its origin in the World Bank's involvement as executing agent of a United Nations Development Program (UNDP) funded "Master Planning" effort by the Water and Power Development Authority (WAPDA) of Pakistan to prepare a "Revised Action Programme" (RAP) for irrigation investments in the basin. This would update the "Action Programme" set out by a similar planning effort in the 1960's.

The resulting Indus Basin family of models has demonstrated a capacity for providing answers to a variety of policy-relevant questions, for example, issues of mechanization, technical change, and agricultural price policy, as well as irrigation system management and evaluation of investment projects and programs. To date these models have been used in three project appraisals in the bank, and there are several more prospective applications of this type. However, these models may well have more potential utility to Government of Pakistan policy makers than to the World Bank. This possibility was noted by the Planning Division of WAPDA, and a team of WAPDA programmers and systems analysts was trained at the bank to effect the transfer of this modeling technology to Pakistan.

The outline of the paper is as follows: the next section presents a description of the Indus model family structure, followed by a review of model validation. These are followed by some results from simulation experiments which analyze conjunctive use in the Indus irrigation system and assess some alternative policies.

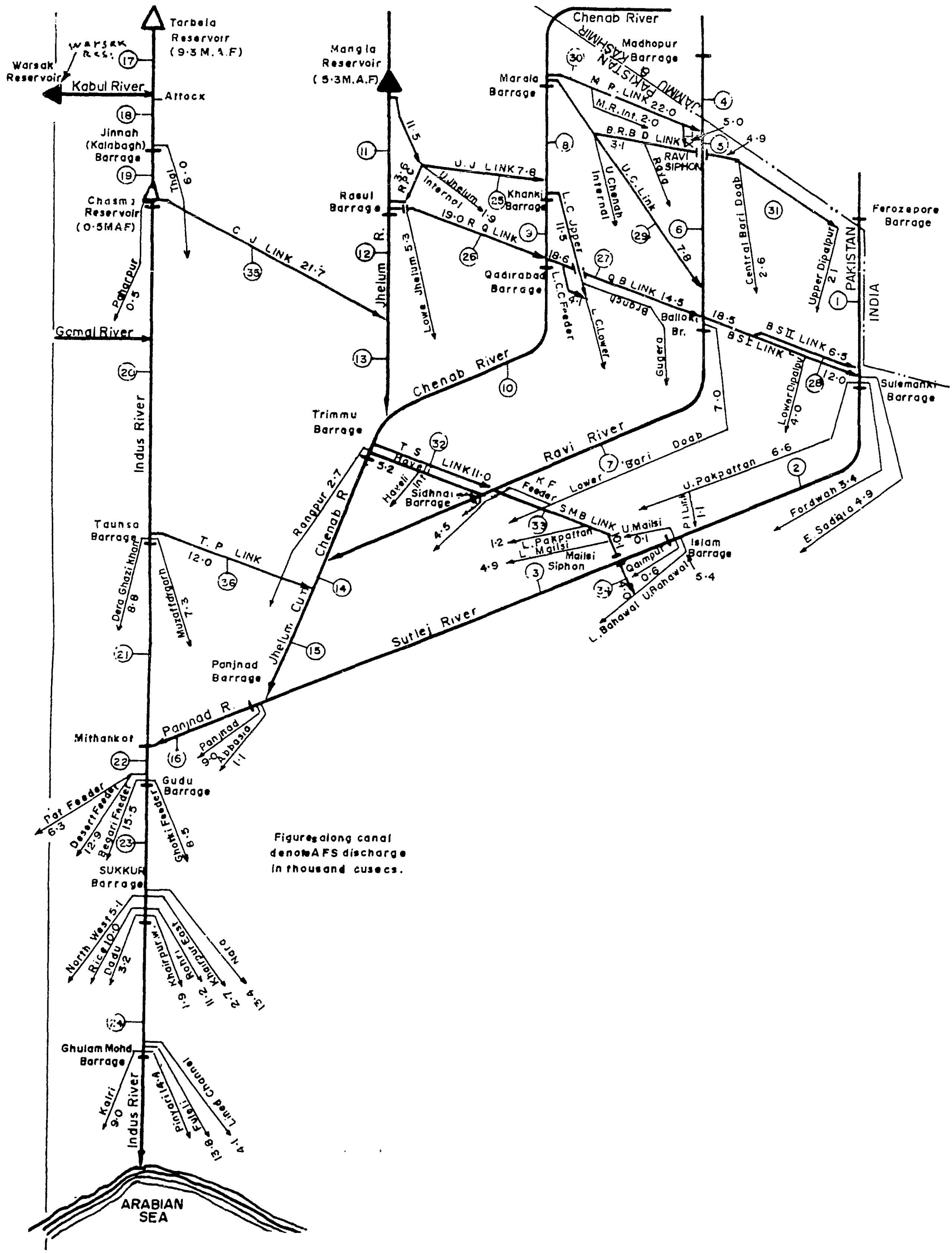

Fig. 1. Structure of the Indus basin irrigation system.

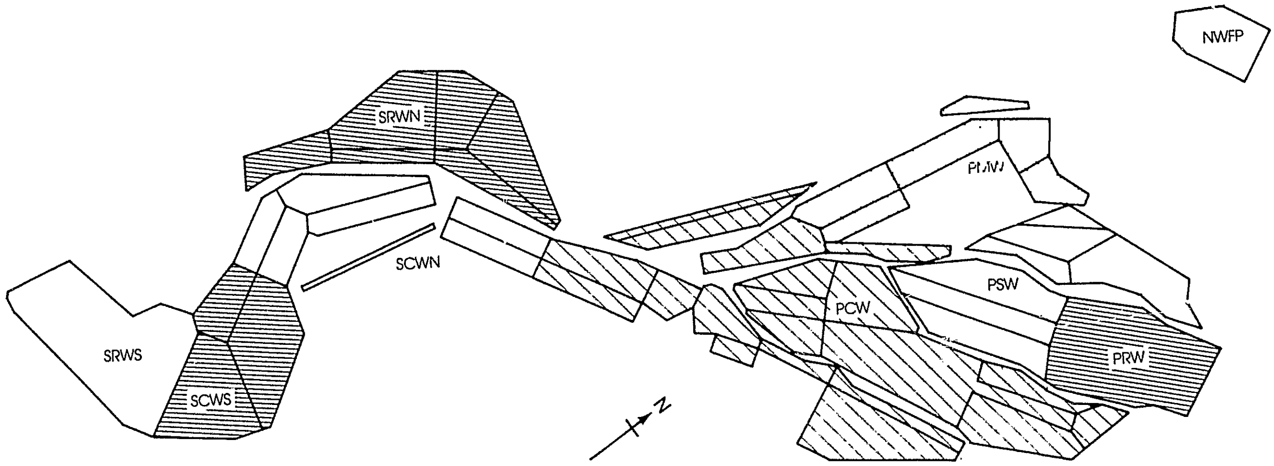

Fig. 2. Pakistan: Indus basin agroclimatic zones.

2. MODEL STRUCTURE

In the past, many economic models concerned with policy and planning have been straightforward optimizing models. While admirably direct, this approach neglects an important aspect of the economic policy environment. 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 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 groundwater) and other inputs, making private investments in tractors, tube wells, etc., and choosing cropping patterns so as to maximize their own welfare. Generally speaking, the strategy of the Indus family of models 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 water–groundwater 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 groundwater 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 groundwater via tube wells 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. Figure 1 presents the schematic diagram of the Indus Basin Irrigation System, which identifies the control points where diversions to individual canal commands are made.

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 agroclimatic zones (ACZ's), and the mapping of polygons into ACZ's is given in Figure 2. The data for the differentiation of the basin into ACZ specific cropping technologies were largely derived from the 2000 farm sample of the Master Planning Agroeconomic survey. Table 1 gives average cropping patterns for the several ACZ's as some evidence of the appropriateness of the partition.

The surface water distribution system must be superimposed on the complex mapping of groundwater areas (i.e., polygons), canal commands, and ACZ's. This is done by means of a network formulation. All of the flows of the schematic for the Indus Basin Irrigation System are represented as directed flows along segments, which are the arcs between one control point or node and another.

In addition to the above-mentioned water constraints, 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 who determine the production and disposition of 11 crops and four livestock commodities. Exogenous resource limitations are imposed on land and labor. The water supply and demand constraint of each farm-level model includes estimates of water available from rainfall, evapotranspiration from the aquifer, and canal and tube well water. When used to evaluate water allocation policies, canal water allocations are endogenous, as is the volume of private tube well pumping. The model maximizes the objective function, which is the sum of polygonal farm incomes less polygonal risk premium terms. The risk term essentially linearizes a nonlinear mean standard deviation of income trade-off surface. Moreover, farm income enters into linear family consumption constraints, and it can be shown that this formulation is equivalent to maximizing a nonlinear utility or weighting function that places great emphasis on meeting family consumption needs.

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. As individual farmers do not recognize their individual effects on groundwater equilibrium which must be maintained over the long run, the government must take into ac-

TABLE 1. Cropping Patterns of Major Crops, Average of 1972–1973 and 1975–1976 Cropping Years: Percent of Cropped Area

	Agroclimatic Zone									
	Northwest Frontier Province	Punjab Mixed Crops-Wheat	Punjab Cotton-Wheat	Punjab Sugarcane-Wheat	Punjab Rice-Wheat	Sind Cotton-Wheat North	Sind Rice-Wheat North	Sind Cotton Wheat South	Sind Rice-Wheat South	Total
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Rice	0.4	2.5	5.2	5.0	30.7	12.5	54.8	8.8	51.0	14.0
Wheat	34.4	52.0	38.5	42.1	41.8	36.3	21.2	41.7	20.5	38.4
Cotton	0.5	8.9	26.2	13.3	2.7	25.8	3.3	30.0	14.8	17.3
Corn for grain	35.0	1.0	1.3	4.1	1.3	0.3	0.1	1.5	0.5	2.5
Gram	0.1	7.3	1.5	1.3	0.8	5.1	10.8	0.1	0.6	2.5
Sugar	18.7	5.0	3.6	8.4	1.9	3.6	0.4	3.7	5.4	4.6
Rape and mustard	0.6	5.1	3.2	1.9	1.4	5.7	3.4	2.6	2.2	2.9
Kharif fodder	3.6	10.0	11.0	10.6	7.0	3.8	0.4	5.4	1.6	8.3
Rabi fodder	6.7	8.3	9.4	13.4	11.1	7.1	5.6	6.2	3.4	9.4
Area cropped, ha × 10^3	336	757	4,745	2,043	1,604	837	931	636	345	12,231
Cropping intensity	158	107	113	121	134	105	106	91	83	114

Sources: 1972–1973 from Agricultural Census Organization, Government of Pakistan, *Pakistan Census of Agriculture, 1972*; 1975–1976 from provincial reports on cropped acreages.

count 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 by *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 tube wells at the level required for groundwater balance.

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 submodels. A model of this size exceeds the capability of existing software for linear programs, and it was apparent early on that a special simplification would be needed. 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 8000 constraints, which is solvable using a large machine and commercial software.

The above introduction has been brief and has ignored many details. Despite this brevity, the reader will have gotten some impression of the site, structure, and complexities that are captured by the system. Readers desiring a complete description of the model structure may obtain this from the authors.

3. Calibration, Estimation of Water Loss Characteristics, and Validation

The Indus Basin Model is a comparative statistical model that simulates producer response to policy intervention. That is, it can be used to compare producer response to different environments where the environmental change is wrought by policy intervention in the sense of complete producer adjustment (i.e., long-run response) to environmental change. Therefore the important function of model validation is not appropriately accomplished when actual historical conditions on a year by year basis are used to simulate a dynamic path of producer adjustment. Rather, average conditions in some base period should be used to generate model solutions that can be compared with an average of actual producer responses in the base period, on the assumption that producer responses on the whole are close to long-run equilibrium.

Two time periods were considered for validation runs, the periods of 1967–1975 and 1975–1980. The former period includes responses that are subsequent to both the introduction of the new green revolution varieties of wheat and rice and the initiation of use of Mangla Reservior and are prior to the initiation of the use of Tarbela Reservoir. The latter period contains the history of post-Tarbela producer responses.

The experiments reported are actually experiments to select a set of water loss parameters that permit the model to acceptably reproduce important aspects of both production response, e.g., the cropping patterns and intensities of Table 1, and the state of the groundwater aquifer. This procedure presupposes prior calibration of the specification of agricultural technology and producer behavior, which was done previously on a polygon by polygon basis. The procedure for calibrating single-farm-level models is well known and need not be discussed here.

The existence of significant uncertainty with respect to the loss characteristics of the surface water system was unanticipated. Perhaps somewhat naively, it had been assumed that these characteristics, which are subject to measurement, would be known with some precision by the operators of a system with as long a history as the surface water irrigation system of the Indus Basin. This assumption turned out to be incorrect.

Our response to the existence of significant uncertainty with respect to loss characteristics of the surface water system was to test the model with several specifications of system loss characteristics representing a spectrum of plausible scenarios concerning system performance. In order to keep the number of validation experiments within reasonable bounds, these scenarios were restricted to specification of a limited number of cases covering the range of likely loss characteristics. The details of the specification of these cases are given in Table 2. Note especially that the high efficiency assumption with respect to watercourse and field losses is at the level specified in the Indus Special Study [*Lieftinck et al.*, 1968], which presents in detail the planning exercise behind the appraisal of the Tarbela Dam project in the mid 1960's. In contrast, the low efficiency assumption with respect to watercourse and field losses is at the level specified in the recently completed Revised Action Programme [*WAPDA*, 1979].

Solutions to the model configured for historical simulation with surface water diversions and reservoir capacity appropriate to the base periods 1967–1975 and 1975–1980 were obtained for the six cases specified in Table 2. The validation experiments specify exogenously the level of the watertable and the surface water allocation for each polygon. Thus one important validation test is whether or not a given water loss specification of the model acceptably reproduces the observed production response of farmers to the historically given gross canal water supplies. Another is whether or not the calculated net recharge is consistent with available evidence on the state of the aquifer. Important aspects of farmer response include cropping patterns, cropping intensities, and livestock holdings.

Considering both production response and the state of the aquifer, our tests clearly pointed to case B_2A_2, i.e., high canal losses, medium efficiency for watercourse delivery and field application, as the scenario with the best estimate of water loss parameters among those considered. Thus the water loss parameters of the B_2A_2 case were accepted as specifying this aspect of the system.

To summarize, the method employed was essentially to impose a rigorous consistency test of model solutions, with consistency defined as conformity with the observed aspects of the Indus Basin Irrigation System in a base period. Given the logical consistency specified by model structure, the additional requirement of empirical consistency with observations from many independent sources is a stringent test. In fact, the severity of this test permitted estimation of unobserved loss parameters when no other method of estimation was available.

4. AN APPLICATION TO SYSTEM MANAGEMENT

One of the major virtues of modeling of any economic system is the capacity that it creates to simulate counterfactual scenarios of system performance. In particular, this capacity permits the investigator to pose penetrating questions with respect to system efficiency. Of course, any effort to assess the efficiency of resource allocation must specify a criterion by which efficiency is to be measured, and this criterion must be acceptable to the people of the country concerned if the assessment is to be meaningful. It is proposed here that the criterion of efficiency be maximization of the sustainable level of agricultural production from available water, given a vector of prices. The qualification with respect to prices is necessary because agricultural production is quite sensitive to relative prices and the model does not provide solutions that are optimized with respect to prices.

TABLE 2. Cases for Sensitivity Analysis of Estimates of Water Loss Parameters

Specification of Losses	
A_1	low canal losses, set at approximately 50% of high losses
A_2	high canal losses, set at 21 percent of pre-Tarbela diversions
B_1	high efficiency at watercourse and field level, set at level approximating that of Lieftinck Report, i.e., 0.65
B_2	medium efficiency at watercourse and field level, set at level approximately 0.50
B_3	low efficiency at watercourse and field level, set at level approximating that of RAP, i.e., 0.395

Canal System Efficiencies*

Case	Efficiency, %
A_1B_1	56.8
A_2B_1	50.6
A_1B_2	43.9
A_2B_2	39.2
A_1B_3	34.4
A_2B_3	30.7

Definitions: A_i are levels of canal losses, $i = 1, 2$; B_j are levels of combined watercourse and field efficiencies, $j = 1, 2, 3$. Cases: A_1B_1, A_1B_2, A_1B_3, A_2B_1, A_2B_2, A_2B_3.

*Assumes diversions of 109.9×10^9 m^3 and high canal losses (exclusive of link canals) of 23.2×10^9 m^3.

TABLE 3. Annual Rim Station Inflows, Indus Basin, 1967–1968 to 1979–1980

RIM Station	Based on Monthly Mean, 1975–1976 to 1979–1980	Based on Seasonal Median, 1967–1968 to 1979–1980
Indus at Tarbela	72.175	72.925
Swat at Chakdara	5.651	5.785
Kabul at Warsak	18.737	19.460
Haro at Gariala	0.973	0.771
Soan at Dhok Pathan	1.759	1.322
Jhelum at Mangla	28.350	27.978
Chenab at Marala	35.774	29.763
Ravi at Balloki	15.471	7.617
Sutlej at Ferozepur	7.804	8.558
Total above	186.692	174.179
Total less Ravi and Sutlej	163.417	158.004

Measurements in m^3 × 10^9.

4.1. *Analytical Framework*

Clearly, a complicated, large-scale simulation model presents problems of interpretation if model solutions incorporate multiple changes. For this reason the sequence of system management experiments has been designed to incorporate only single changes (from some reference case) in each experiment. A number of the specifications of the experimental sequence are essentially imposed by the choice of efficiency criterion, i.e., maximization of the sustainable level of agricultural production from available water given a vector of prices. For example, the water endowment of the system from rim station inflows must be specified in terms of the best available estimates of long run supply (in terms of some appropriate measure of central tendency). For this reason the water endowment at rim stations for the sequence of experiments is specified as the monthly flows of the median season over the period from 1967–1968 through 1979–1980 at each of the rim stations, with Ravi and Sutlej flows deleted since title to these was given to India in the Indus Waters Treaty of 1960. The resulting estimates (for annual flows) are presented in Table 3.

For convenience the vector of prices prevailing in 1976–1977, the period for which much of the data base was collected, was chosen as the exogenous price vector. Comparison established that relative prices in other years were similar to those prevailing in 1976–1977 except for petroleum products and one agricultural commodity whose world price has a very large variance. In order to provide a test of model sensitivity to the price vector used as well as an indication of the long run equilibrium effects of the large increase in the relative price of petroleum that occurred in 1979–1980, several experiments employed the price vector prevailing in 1980–1981.

TABLE 4. System Management Experiments

Water Endowment and Loss Parameters	Prices	Pre-Tarbela Allocation as Lower Bound to Canal Water Allocation				Pre-Tarbela Income as Lower Bound to Farm Inc.	No Distributional Constraints	
		Polygonal		Provincial				
		Month	Season	Month	Season		With GWB	Without GWB
Monthly flows based on 1967–1980 seasonal median without Ravi and Sutlej	1976–1977	J	Q	S	T	M	O	P
Monthly flows based on 1967–1980 seasonal median without Ravi and Sutlej	1980–1981	K						
Monthly flows based on 1967–1980 seasonal median without Ravi and Sutlej	plus 50% energy inc.	L						
Monthly flows based on 1967–1980 seasonal median without Ravi and Sutlej plus WC loss adjustment	1976–1977	R						

The sequence of experiments that provide the framework for the analysis of system management are laid out categorically in Table 4. Experiment J is the base case in the analysis of system management. The experiments listed to the right of experiment J constitute the main sequence of single step variations in water allocation policy. Thus, experiments J, Q, S, and T all specify a minimum water allocation based on historic water rights, where these are defined operationally as the mean diversion over the pre-Tarbela (but post-Mangla) period, 1967–1975. However, experiments J and Q specify historic water rights in terms of each polygon, while S and T specify historic water rights only at the provincial level. Similarly, J and S specify monthly and Q and T specify seasonal water rights. Experiment M substitutes the level of farm income derived from a pre-Tarbela model solution as a lower bound to farm income in place of the historic water rights constraint. Experiments O and P drop all explicit distributional constraints, with O including and P excluding the groundwater balance constraint. Strictly speaking, experiment P does not provide meaningful long-run water allocation, but it is included to show the effect of dropping the groundwater balance constraint. The experiments listed below experiment J in the third column of Table 4 retain J's specification of long-run rim station inflows and the historic water rights constraint in the form of a monthly polygonal lower bound on canal diversions but vary prices or water loss characteristics. Experiments K and L substitute 1980–1981 prices for 1976–1977 prices, and in addition, L increases energy prices by 50% and drops the subsidy on fertilizer use. Experiment R differs from experiment J in that losses along water courses have been adjusted to reflect watercourse improvement and/or rehabilitation, as specified by the On Farm Water Management Project, a credit to Pakistan which was recently approved by the World Bank.

TABLE 5. Real Agricultural Value Added, Indus Basin

Experiment	Total	Fresh Groundwater Areas	Saline Groundwater Areas
		Value Added	
D	100.0	100.0	100.0
J	116.6	101.9	155.1
M	119.7	103.3	162.1
O	119.5	103.1	162.2
P	120.1	103.1	164.5
Q	118.4	102.4	159.9
R	120.5	104.4	162.4
S	119.3	102.9	162.1
T	119.5	103.1	162.2
		Employment	
D	100.0	100.0	100.0
J	113.6	103.2	144.6
M	115.1	103.7	149.4
O	115.1	103.7	149.4
P	116.1	103.6	153.8
Q	114.3	102.9	148.6
R	115.9	104.5	150.0
S	115.1	103.6	149.3
T	115.1	103.7	149.4

Measurements as percent of post-Tarbela level.

4.2. *System Management Experiments*

The experiments specified in Table 4 were completed with the model configuration in a water-optimizing mode, i.e., solved for an endogenous water allocation. Since the experimental solutions maximize farm income subject to farmer preferences with respect to family subsistence requirements and risk aversion, these solutions represent the maximum agricultural production that can be obtained given model specification and farmer preferences and hence correspond to the efficiency criterion adopted. In all experiments, existing stocks (i.e., 1975–1976) of private tube wells and tractors are given as initial conditions, and these stocks can be augmented by endogenous private investments. The groundwater balance constraint is imposed in all experiments except P. This implies that the value of the dual variable corresponding to this constraint (i.e., shadow price) is the implicit tax or subsidy that is required to induce farmers to pump their tube wells at the level required for aquifer equilibrium. This tax or subsidy must actually be imposed, at least indirectly, for the model solution to be meaningful. Similarly, in the saline groundwater areas the objective function of the polygonal submodels includes a term for drainage costs. The interpretation is that farmers in these areas demand that amount of canal water diversions which maximizes their utility, given public drainage costs for which they expect to pay in the form of some kind of tax. Since the government controls the canal water diversions, it is not actually necessary that this tax be imposed in order to induce the desired level of agricultural production. It is necessary, however, that drainage costs be taken into account in determining the efficient water allocation. In the model this is done by assuming that the government has social welfare objectives which are completely consistent with maximizing farm output subject to farmer preferences. In this fashion the two-level programming problem discussed by *Bisschop et al.* [1982] can be solved in a linear programming model, i.e., the physical externality imposed by the groundwater aquifer can be internalized via a tax or subsidy.

4.3. *Effects of System Management Policies on Production and Factor Utilization*

Production is measured in terms of value added, and since our concern is efficiency, i.e., relative performance, production is measured relative to experiment D, which approximates actual post-Tarbela conditions. In additon, results from experiments K and L are not presented here in order to confine discussion to policies directed toward changes in water distribution. The effect of the several such policies specified in Table 4 on agricultural value added and employment is given in Table 5. Note that while the overall gains range from 17% to 20% above the post-Tarbela level for value added and from 14% to 16% for employment, the gains are markedly different between fresh groundwater (FGW) areas and saline groundwater (SGW) areas. The former show increases of only 2% to 4% for both measures, while the latter have gains of 55% to 65% in value added and from 45% to 54% in employment.

TABLE 6. Labor and Land Input Intensity by Groundwater Quality area

	Labor Intensity[a]		Land Intensity[b]	
Experiment	FGW Areas	SGW Areas	FGW Areas	SGW Areas
		Indus Basin		
D	431	276	138	101
J	445	399	141	138
M	447	413	140	143
O	447	413	140	144
P	446	425	140	144
Q	443	410	140	142
R	450	414	142	144
S	446	413	140	144
T	447	413	140	144
		Punjab		
D	427	235	135	80
J	441	347	137	118
M	444	375	138	125
O	444	375	138	125
P	445	404	138	130
Q	439	378	137	126
R	447	368	138	126
S	443	374	138	125
T	444	375	138	125
		Sind		
D	396	308	154	117
J	415	440	158	154
M	405	442	149	158
O	407	442	149	158
P	392	441	148	154
Q	418	435	161	154
R	418	450	160	158
S	405	442	149	158
T	407	442	149	158

[a]Defined as man-hours of labor input per acre.
[b]Defined as cropping intensity or cropped acres per acre of irrigated land, normalized to a percentage scale, where 100 denotes each irrigated acre is cropped once a year.

TABLE 7. Water Supply per Hectare (at Root Zone)

	SGW Areas		FGW Areas		
Experiment	Public-Supplied	Total	Public-Supplied	Private Tubewells	Total
		Indus Basin			
D	0.579	0.762	0.378	0.348	0.857
J	0.786	1.046	0.381	0.366	0.881
M	0.774	1.039	0.372	0.351	0.860
O	0.759	1.024	0.372	0.348	0.857
P	0.774	1.042	0.390	0.326	0.857
Q	0.753	1.024	0.390	0.354	0.881
R	0.860	1.131	0.418	0.332	0.893
S	0.786	1.055	0.375	0.351	0.863
T	0.759	1.024	0.375	0.351	0.863
		Punjab			
D	0.357	0.451	0.326	0.372	0.814
J	0.494	0.631	0.326	0.390	0.838
M	0.537	0.686	0.332	0.381	0.835
O	0.537	0.686	0.329	0.378	0.832
P	0.561	0.719	0.338	0.372	0.835
Q	0.537	0.689	0.332	0.354	0.841
R	0.533	0.692	0.360	0.363	0.850
S	0.537	0.686	0.329	0.381	0.832
T	0.537	0.686	0.329	0.381	0.832
		Sind			
D	0.750	1.006	0.744	0.235	1.192
J	1.012	1.366	0.780	0.226	1.222
M	0.957	1.314	0.710	0.171	1.091
O	1.006	1.286	0.710	0.171	1.094
P	0.942	1.292	0.820	0.046	1.055
Q	0.924	1.280	0.796	0.186	1.201
R	1.110	1.472	0.881	0.143	1.247
S	0.982	1.341	0.710	0.171	1.091
T	0.930	1.286	0.710	0.171	1.094

Measured in meters. The number given is the delta, or height of total water applied per unit of level land. Thus a delta of one implies an application of 10,000 m^3 ha^{-1} (measured at the root zone).

The striking difference between the output responses of FGW and SGW areas clearly signals similar shifts in resource utilization, and Table 6 presents some results on the intensity of use of labor and land. Note that the data from the post-Tarbela simulation (experiment D) show divergent levels of input intensity for both inputs between FGW and SGW areas. At the level of the entire basin the effect of alternative system mangement policies is to bring the levels of input intensity much closer to equality between the two groundwater quality regions, with this being accomplished by large increases in intensities for the SGW areas and relatively small increases in the FGW areas. However, when these data are disaggregated by major provinces, the picture is somewhat different. In Punjab, while the trend remains the same, the SGW areas lag significantly behind the FGW areas in input intensity under all policies. On the other hand, in Sind the SGW areas show greater input intensities under most policies. Thus the SGW areas of Sind show much higher input intensities than do the SGW areas of Punjab.

The reason for these divergent patterns becomes clearer when relative water supplies are taken into account, and these data are shown in Table 7. As might be expected, water supply per acre also shows a pattern of large increases in the SGW areas and small increases in the FGW areas under all water allocation policies. However, the quantity available per acre in

TABLE 8. Public Costs of Aquifer Control Under Groundwater Balance

Experiment	Private Tube Well Tax (−) or Subsidy (+)	Annual Cost of Drainage	Total Public Cost	Cost Per Caput of Farm Population, rupees
J	828.4	374.0	1,202.4	50.3
M	612.6	417.2	1,029.8	43.1
O	665.7	418.0	1,083.7	45.3
Q	425.7	411.6	837.2	35.0
R	807.0	290.2	1,097.2	45.9
S	687.9	415.8	1,103.7	46.2
T	684.4	418.1	1,102.5	46.1

Costs in 1977 rupees × 10^6.

Sind SGW areas is almost twice as large as in Punjab SGW areas. In fact, both the FGW and SGW areas in Sind show significantly greater total water supplies than the corresponding areas in Punjab under all policies. This is a surprising outcome since it is often argued that the interprovincial distribution of surface water is skewed toward Sind because of political factors. Yet these experiments, which include some which release all distributional or equity constraints, show the same pattern of relatively greater distribution of surface water in Sind. It might be argued that the physical capacities of the irrigation system for diversion at various points have constrained the model solutions to this outcome. However, when the shadow prices on capacities of link and main canals are examined, this turns out not to be true to a significant degree. Part of the difference in available annual supplies is due to significantly greater subirrigation in Sind, which is an uncontrollable (by farmers) source that peaks in months when farmers have relatively little land under crops. Yet canal diversions to SGW areas are significantly greater in Sind, and this circumstance argues for greater marginal productivity of water there. One factor contributing to high productivity in this region of Sind is its comparative advantage in rice cultivation, which has benefited importantly from the introduction of the high-yielding new varieties. Thus the high productivity of inputs in the water-intensive rice crop has resulted in significantly higher optimal diversions to the SGW areas of Sind.

4.4. *Effects of System Management Policies on Farm Incomes, Public Aquifer Control Costs and Resource Prices*

Since per capita income is a useful and frequently used measure of economic development, albeit an imperfect one, a review of the impact of the system management experiments on per capita farm incomes has considerable interest. Note, however, that the necessary existence of transfer payments due to the implicit tax or subsidy on tube well pumping somewhat complicates the concept of farm income. Thus a distinction must be made between income from farm operations proper, i.e., unadjusted income, and income that allows for the impact of the tax or subsidy, i.e., adjusted income. The annual public costs of aquifer control for each of the system management experiments are given in Table 8. These costs, which are largely subsidy costs, range from 800 to 1200 × 10^6 rupees per year. Adjusted per capita incomes by provinces and groundwater quality zones are given in Table 9, which shows that Sind incomes are greater than Punjab incomes for both groundwater quality zones and under all policies. Basin wide adjusted per capita incomes show increases of 19% to 22%, with increases ranging from 2% to 13%, in the FGW areas and from 46% to 84% in SGW areas. Unlike the current post-Tarbela situation, per capita incomes are greatest in Sind SGW areas under all policies, and incomes in Punjab SGW areas are slightly greater than in Punjab FGW areas under most policies. Thus, although the objective was more efficient resource utilization, the alternative policies have significant income distributional implications by water quality zone, with something close to equality between zones achieved in Punjab and a reversal of the present situation in Sind. Note, however, that in absolute terms, every zone gains in per capita income. In addition, the public costs of aquifer control per head of farm population, which range from 35 to 50 rupees, are small in relation to the gains in per capita incomes.

Of course, the impact of the alternative policies on the incomes of the several groups within a region may be adverse. Some information on income distributional impacts by class is available in the form of the shadow prices on the land and water constraints. These data are summarized in Table 10. Note the very large increases in the implicit land rents in the SGW areas under all of the alternative policies and the corresponding sharp decreases in water prices in these areas. A similar pattern occurs in the FGW areas, but as expected the magnitudes of the changes are much smaller. It seems clear that landowners, especially in the SGW areas, are well positioned to capture much of the increase in farm incomes. The extent to which tenants and landless laborers benefit from the increase in aggregate farm production depends on the relative change in the demand for and supply of farm labor.

The results from experiments K and L, which were run using 1980–1981 prices, were very similar to the results from experiment J, which differs from them only in the price param-

TABLE 9. Per Capita Income (Adjusted)

		Punjab		Sind	
Experiment	Indus Basin	FGW Areas	SGW Areas	FGW Areas	SGW Areas
D	1,081	1,125	708	1,473	1,222
J	1,284	1,188	1,129	1,623	1,780
M	1,307	1,196	1,230	1,613	1,816
O	1,309	1,197	1,231	1,620	1,816
P	1,288	1,151	1,305	1,585	1,800
Q	1,323	1,216	1,209	1,664	1,837
S	1,308	1,195	1,230	1,643	1,816
T	1,309	1,196	1,231	1,650	1,816

Income in 1977 rupees.

TABLE 10. Annual Shadow Prices of Land and Water

		Punjab		Sind	
Experiment	Indus Basin	FGW Areas	SGW Areas	FGW Areas	SGW Areas
		Land, 1977 rupees/ha			
D	578	781	30	916	143
J	892	904	289	1,213	1,065
M	993	892	588	1,233	1,405
O	983	877	588	1,230	1,403
P	904	810	590	1,072	1,225
Q	931	865	462	1,255	1,242
R	993	926	420	1,272	1,400
S	983	874	583	1,230	1,400
T	986	877	585	1,230	1,400
		Water, 1977 rupees/m³			
D	1.671	1.233	3.299	0.895	2.583
J	0.997	0.952	2.178	0.525	0.874
M	0.884	1.030	1.543	0.605	0.448
O	0.870	0.993	1.544	0.609	0.457
P	0.999	1.112	1.403	0.822	0.701
Q	0.953	1.033	1.802	0.457	0.683
R	0.799	0.873	1.748	0.438	0.483
S	0.861	1.007	1.553	0.612	0.454
T	0.860	0.993	1.544	0.610	0.459

Annual shadow prices are sums of shadow prices of respective monthly constraints of polygonal submodels aggregated into weighted averages for the areas shown.

eters. The important change in relative prices (and only these matter for the model) in these experiments is a sharp increase in the prices of fuels and fertilizer. These changes in costs reduce value added and farm income slightly for experiment K and significantly more for experiment L, which raises energy prices by an additional 50%. Since these changes directly affect private tubewell operating costs, the resulting increase in the optimal pumping subsidy caused the public costs of aquifer control to increase by factors of 2 and 4 in K and L, respectively.

In order to test the sensitivity of the results from the system management experiments to the model assumptions with respect to drainage costs, experiment J was repeated several times with drainage costs increased to 1.5, 2, 3, 5, and 10 times the original level. In these experiments, public costs of aquifer control increased (in the above sequence) by 10%, 29%, 54%, 103%, and 168%, and per capita incomes in the SGW areas decreased by 0.3%, 1%, 2.5%, 4.5%, and 9% (in the same sequence). Overall farm income remained virtually constant throughout this sequence of experiments, with increases in the FGW areas offsetting decreases in the SGW areas. Thus the results from this sequence of experiments have demonstrated that the model results are robust with respect to drainage cost estimates.

5. SUMMARY

Large gains in agricultural production and employment for the Indus Basin are possible given more efficient allocation and management of surface and ground waters (i.e., 17%–20% in output and 14%–16% in employment). These gains 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 groundwaters. Necessary steps to achieve efficient conjunctive use are (1) enabling investments in drainage works in saline groundwater areas and (2) eventual public control of private tube well 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 utilizations. The subsidy costs (shown in Table 8) might be unnecessary in practice, since simulation experiments have shown that improved agricultural technology shifts the optimal control from a subsidy to a tax. However, large drainage investments will be required to achieve the gains shown, since these depend on large increases in canal diversions to saline groundwater areas. Until such drainage investments are in place, only limited gains are possible from increases in canal diversions. Control over private tube well pumping is not needed at present since subsidies to encourage greater pumping are unnecessary until significant increases in drainage capacity exist; and with present depths to water table of less than 20 feet (6 meters) in almost all fresh groundwater areas, a need for taxation to discourage excessive withdrawals does not yet exist.

Acknowledgments. The views and interpretations in this paper are those of the authors and should not be attributed to the World Bank, to its affiliated organizations, or to any individual acting on their behalf.

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J. H. Duloy and G. T. O'Mara, Economics and Policy Division, Agricultural and Rural Development Department, World Bank, 1818 H Street NW, Washington, DC 20433.

(Received March 6, 1984;
revised July 19, 1984;
accepted July 23, 1984.)

THE WORLD BANK

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ISSN 0253-2131