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10. Abstract

This study is a part of the "Grow More Food" campaign of our civilization for world peace and prosperity. It provides a working mathematical model for analyzing and optimizing the conjunctive use of surface and ground water resources of West Pakistan. In specific terms, the objective of the study is to determine the size of the canal system, the surface reservoir, and the ground water pumping facilities, such that, when the system is operated optimally, the capital and operation and maintenance costs of meeting the given irrigation water requirements are minimized. The results of this research indicate that by optimal conjunctive use management of the Indus Basin Irrigation System in Pakistan, the available water resources can be used more efficiently and at a lesser cost; the ground water aquifer can serve as a functional reservoir and a recycling facility, considerably increasing the usable water resources; and the present "use-when-available" supply system could be developed into a "supply-on-demand" system. This will make other technological, social, and economic inputs more effective and meaningful. As a result, the agricultural produce in the country could potentially be increased by 5 to 6 times. Continued research extension and development are necessary to explore this potential and determine its attainability. The scope of this study is limited to only a relatively small subset of the overall conjunctive use problem in West Pakistan. Some other problems, however, are identified and suggested for future research.

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CONJUNCTIVE USE OF INDUS BASIN WATERS - PAKISTAN: A GENERAL SUMMARY OF Ph.D. DISSERTATION

Water Management Technical Report No. 30

by

Mohammad Talib Chaudhry

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"Water Management Research
in Arid and Sub-Humid Lands of the
Less Developed Countries"

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CONJUNCTIVE USE OF INDUS BASIN WATERS PAKISTAN

Introduction

Food is a pressing need in most countries of the world. The problem is, however, particularly serious in countries with less developed economies. In these countries low agricultural produce is combined with high intensity of fast growing population. Experts in the United Nations Food and Agricultural Organization seriously warn that unless something is done and done soon, a painful famine in vast areas of the world may be around the corner. In the past, famine conditions have been averted in India, Pakistan, Afghanistan, Southeast Asia and numerous other countries by generous food imports from the USA and Canada. The surpluses in the USA and Canada, however, may not be sufficient to match possible world-wide deficits in the future. In fact, even at present, most of the people in most of the countries with less developed economies, suffer from under-nourishment.

Potentially, there are two complementary options available to overcome the food problem. One is the population control. The technology of birth control is already well developed and further advances in the field are in process. The need for socio-economic guarantees and substitutes for large numbers of children in a family, to provide old age care and security, is increasingly being recognized. Resistance to birth control exists in some countries in the name of religion and morality, but the moral logic and the divine religiosity are unquestionably on the side of population control. The essence of moral issues is the sanctity of human life. Seen in this light, birth control which prevents some potential lives from coming into being, is far better than the painful starvation of human life after it comes into being; worse still is to remain unconcerned about this situation! Population stabilization is essential in any "food for the world" program. The lesson will be learned in time but it will be unfortunate if it is learned after a catastrophe.

The other potentiality that humankind possesses is the ability to increase the food production, at least several times over the present supply. Numerous inputs are necessary to fully realize this potential. Water being a basic input in the "food production system", a water management research project was instituted in 1968 under a grant by AID to Colorado State University. The field work was initially limited to Pakistan, but application of the project results should extend to all the developing countries.

As a part of the water management research project, an attempt has been made by the author to prepare an optimizing model for the conjunctive use of the surface and ground water resources of the Indus Basin in Pakistan. This report is a general summary of the author's Ph.D. dissertation, "Conjunctive Use of Indus Basin Waters Pakistan". Written primarily for nontechnologists, many of the technical aspects have been omitted. Emphasis is placed on the relevancy of the conjunctive use to the food production, its advantages and potentialities. An attempt has been made to show that the research on the conjunctive use optimization is important both for immediate and long run planning of water resources development and management. Readers who are interested in more details may see the detailed dissertation report and the specialized papers that the author intends to write on the various aspects of his research work.

On Farm Research

One of the requirements of AID has been to limit the water management research project to "on farm" research. The author has categorized his research as "on farm" research in the sense that it attempts to identify and meet an "on farm" water management need. In other words, use is made of the "problem identification and problem solving" research approach, where the problem is an "on farm" problem. In fact, most "on farm" research needs to be so defined. There are on farm needs or requirements essential for increasing the farm yields. These needs may be considered

as "farm bound". The solutions to meet these "on farm needs", however, are not "farm bound". The supply channels generally come from outside the farm. Consider for example, the problem of "seed quality". Once the problem of providing better quality seeds is identified as an "on farm" need, the problem cannot be left there or else the effort will be worthless. Now it does not need much argument to see that many of the actions required to produce, control, preserve and supply "quality seeds" are not "farm bound". The supply channels for quality seeds, as stated before, will, in general, have to be arranged from outside. Even when in an ideal case the quality seeds can be grown, controlled, preserved and supplied locally by some type of farmers organization, the socio-economic and legal actions required to create and make such organizations functional are not "farm bound". In an economically efficient real world situation, the market structure which lies outside the farm cannot be ignored for the supply of the quality seeds. Thus both the identification of the "on farm" need for the quality seeds and investigating the arrangements for their supply channels are essential for a meaningful research on the subject. So is the case with most other social, economic, legal, managerial, agronomical and physical inputs.

It is evident from the foregoing definition and explanation that the "on farm research" is very broad in scope. In the author's opinion, the breadth of scope of the on farm research program is its real and valuable asset. It makes this research amenable to interdisciplinary approach and thus distinguishes it from the earlier efforts to increase food production in Pakistan and other countries with less developed economies.

Water Among Agricultural Inputs

Water is the web of life. Man has always known that he must have water to live. In this day of rapid scientific advancement, he has realized that he is more dependent on water than ever before. He knows that to provide himself with the water he wants, where he wants it, fit to use as he wants to use it, and available at the time he needs it, he will have to work more than ever before, and spend money as never before. The water management research project at Colorado State University is a response to this awareness.

The existing Indus Basin Irrigation system in Pakistan is primarily dependent on run of the river supplies. Two major storage dams, Mangla (completed in 1967) and Tarbela (under construction) form a part of the Indus Basin Replacement Plan, and do not materially change the run-of-the river characteristics of the system. As a result, there is a considerable degree of uncertainty in the quantity and the timing of the irrigation water supply. In addition, there is a general shortage of irrigation water, particularly, during the sowing and maturing periods.

The climate and the soils of the region would permit an irrigation intensity of 200%*or more in most areas. The present cultivation, however, is limited to only about 85% irrigation intensity. This means that more than half of the cultivable canal command areas lie fallow during each of the two cropping seasons Rabi (winter) and Kharif (summer). Even the crops sown do not get adequate water supply. Consequently, the crop yields per acre, particularly during relatively dry years, is very low. The average yield per acre in Pakistan is about one-third of that in similar areas in USA, Egypt and certain other agriculturally developed countries.

Except for the localized areas, the most efficient and economic way to increase the agricultural produce in Pakistan is to increase the cultivation intensity on the one hand and the yield/acre on the other, within the present canal command areas. To increase the yield/acre, a number of inputs are necessary. These include quality seeds, fertilizers, improved agricultural implements, herbicides, insecticides, better social and management institutions,

*i.e. 2 crops/year

better legal framework, better educational and extension facilities and above all adequate and assured irrigation water supply. Without adequate and assured irrigation water supply, the potential of the other inputs cannot be fully realized. The author is rather of the opinion that under inadequate and uncertain irrigation water supply, any significant investments in other agricultural inputs may lead the Pakistani farmers, most of whom exist at subsistance level, to a situation of the "gamblers ruin problem". The maxim of the gamblers ruin problem is that those who have no capacity to survive a risk, should not take the risk.

The foregoing discussion points out that although many inputs are required to increase the agricultural produce in Pakistan, the inadequate and uncertain irrigation water supplies impose an over-riding constraint, which must be overcome before other inputs can be effectively used.

The Importance of Conjunctive Use in Water Management Research

The optimal conjunctive use of surface and ground water offers a great potential for enhanced and assured water supplies of acceptable quality at minimum cost. There is hardly any differing opinion on this. "Future demand for water requires planning for maximum utilization of all existing supplies. This can most economically be attained by conjunctive use of surface and ground water reservoirs" (Todd, 1965). "Maximum development of water resources requires conjunctive utilization of surface and ground water resources" (Buras and Hall, 1961). "Surface and ground water are inextricably intertwined and are not to be arbitrarily separated" (Kazmann, 1951). These are only a few of the enlightened opinions on the subject.

The use of the surface reservoirs for the conservation and use of the surface water resources is a well established practice. Ground water aquifers have also long been recognized as an important source of water. However, in the past, subsurface reservoirs have been used with almost complete disregard of the surface storage and interrelationships between the two. Only recently, attempts have been made to understand the interaction between the surface and ground water and to establish a rational basis and procedure to analyze the conjunctive use of the two resources.

In most arid and semi-arid areas, large underground storage reservoirs exist. They can be used with advantage in conjunctive use management and operation. It is important to recognize in this connection that the ground water aquifer can be used as a functional storage reservoir as it can:

1. Admit water. Ground water recharge is the mechanism through which the aquifer reservoirs admit water. The author recommends that further research be carried out on this aspect as it is crucial to the optimum use of the aquifer storage.
2. Store water The subsurface water movements and water quality need to be carefully studied.
3. Deliver water when needed. Ground water pumping is the mechanism through which the water stored in the aquifer can be used.

The three basic requirements of a functional reservoir, i.e., the ability to admit, to store, and to deliver water, are met both by surface and aquifer reservoirs. The surface and aquifer reservoirs, however, differ in ways in which they admit, store and deliver water. The conjunctive use enables the best use of these differing characteristics under different conditions. the aquifer reservoirs are effective in cutting down the evaporation losses that are of considerable concern in the case of surface reservoirs, particularly when the latter are used for long term storage. The underground aquifers also provide a degree of recycling of water use and thereby effectively increase the utilizable total water resources. On the other hand, improper management of a water system can lead to a complete destruction of the aquifer as a storage reservoir and a source of water of acceptable quality and as a generator of water resources through recycling.

Surface and ground water are inextricably intertwined and should not be arbitrarily separated. Such a separation may result in damaging consequences. To the author's mind, the questions like modification or lining of the water courses;[1] determination of the cropping patterns; planning for water

[1] The lining of water courses in fresh water areas is of questionable economic value, which needs further research of the available alternatives.

applications to prevent leaching down the fertilizers, or to leach down the salts to prevent their accumulation on the surface; installation of new tubewells and recharge of the aquifer to supply the necessary water; the water quality management; the timing of irrigation supplies; building efficient management institutions; and scores of other related questions, cannot be decided upon without having deeper insights into the entire water resources system and its potentialities of which the conjunctive use of surface and ground water is an integral and probably the most important part.

The Indus Basin Irrigation System

The area of interest in this research is West Pakistan with a population of some 65 million people. It is situated between longitudes 61 degrees and 75 degrees east and latitudes 24 degrees and 37 degrees north. Bounded by Iran on the west, Afghanistan on the northwest and north, China on the northeast, India on the east and southeast, and the Arabian Sea on the southwest, West Pakistan has a total area of 405,700 square miles. This includes 95,300 square miles in Gilgit Agency, Baltistan and Azad Kashmir Of the total, about 255,700 square miles comprise rugged mountain terrain, narrow valleys and foothills. The remaining 150,000 square miles consist of sandy desert and flat alluvial plains, of which some 75 million acres or 117,000 square miles area is estimated to be arable, with over 50 million acres included in what is known as the Indus Plains.

Geographically West Pakistan falls entirely within temperate zone but the climate is, in general, tropical or subtropical. Summer temperatures throughout most of the Indus Plains are high, with temperatures exceeding 115°F not unusual. The winters are chilly but mean monthly temperatures during winter months range between 50°F and 60°F and seldom drop to freezing points in most of the areas. Mountainous and coastal areas, however, are exceptions in some respects.

The rainfall is highly variable in time and space and in most of the area is inadequate to support cultivation. The mean annual precipitation ranges from less than 4 inches in the southern parts to more than 35 inches at the

foothills of the mountains in the north. Most of this precipitation is concentrated in the July to September monsoon period, when torrential rains may produce a third of the year's rainfall in a day. The rainfall stored in the soil to meet the consumptive use requirements of crops is thus much smaller than the total precipitation.

Snow and glacier melt in the mountains in summer and the rainfall which is heavily concentrated in monsoon season, feed the Indus river system. The river flows, though perennial, are variable within a year and from year to year.

The Indus Plains, which form an outstanding physical feature of Pakistan, contain one of the world's oldest and largest irrigated areas. The system as it stands now consists of some 38,000 miles of irrigation channels, and a series of barrages and canal headworks which control the diversion of river flows into the canals. Many of the canals are very large. Fifteen have a capacity of 10,000 to 24,500 cfs. Included in the system are 8 new inter-river link canals totalling 400 miles in length and 128,100 cfs in capacity. These have been constructed to replace the water in the three eastern rivers, which have been apportioned to India under the Indus Water Treaty of 1960. In the same connection, two major storage reservoirs have been constructed with usable capacities of 4.2 and 8.6 MAF respectively. The total inter-river transfer capacity, including the new and the old links, now stand at 4.2 MAF/month. A schematic presentation of the system is given in Fig. 1.

The Indus irrigation system covers a total of about 33.5 million acres of cultivable command area. It is primarily a run-of-the-river system. The two reservoirs, Mangla and Tarbela, being a part of the Indus Basin replacement plan do not materially change the characteristics of the system. The average annual river diversions are of the order of 85 MAF per annum. They will increase to about 95 MAF by 1975, after completion of Tarbela dam. This use is out of about 142 MAF average annual flow in the Indus system, measured at rim stations. There is thus about 47 MAF of unused river flow on the average, which is presently wasted to sea in the shape of floods. This can be developed for useful purposes.

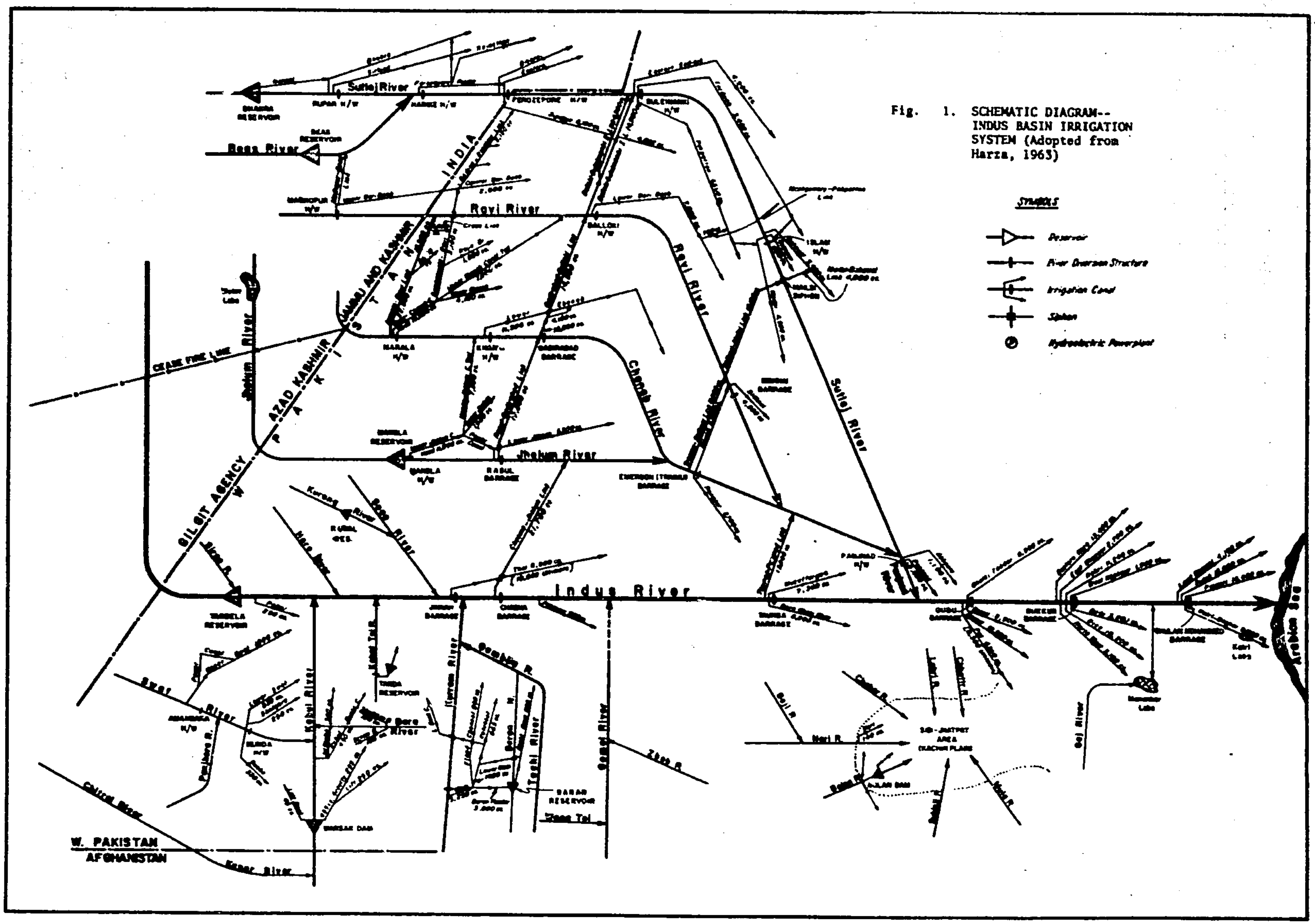


Fig. 1. SCHEMATIC DIAGRAM--INDUS BASIN IRRIGATION SYSTEM (Adopted from Harza, 1963)

Another major water resource in the Indus Basin is the vast aquifer The gross area of this aquifer is about 50 million acres or 78,000 square miles, about 75% of which underlies the area developed for irrigation. Some 19 million acres of the irrigated area is underlain by ground water, having a salinity of 3000 ppm or less, which is useable for irrigation. Of this, about 14 million acres are underlain by ground water having a salinity of less than 1000 ppm, which could be used directly. The ground water in the remaining 5 million acres can be used after mixing with canal water. Judging from the small number of boreholes that have reached the bedrock, the depth of the aquifer exceeds 1000 feet in most areas. The uppermost 100 feet of the aquifer with usable water quality, contains some 300 to 400 MAF of ground water. This estimate is based on an aquifer storage coefficient of 0.15 to 0.25, used in various reports on the subject. A storage coefficient of 0.20 has been adapted for the purpose of this study.

The Physical Model for Conjunctive Use Optimization

The details of the conjunctive use optimizing model prepared for this study are given in the main dissertation report. Following is a brief description of it.

1. System Decomposition: The Indus Basin irrigation system is a very complex system. Modeling this entire system is much beyond the scope of a single Ph.D. dissertation. Even otherwise preparing a single model for the whole system may not be feasible. Using the decomposition and multilevel optimization concepts, however, one can decompose the large scale and complex Indus Basin irrigation system into a number of subsystems. Each of these subsystems can be optimized independently and the results can then be combined to achieve an optimal solution to the whole system. This is a theoretical visualization. In practice, the process of decomposition and reintegration may be very complex and may involve certain nonoptimalities, where the matured judgement and the insights into the system will be best of the guides. In spite of this type of imperfections, the analytical optimization models visualized as above can make a detailed analysis of the system or possibly provide new insights into the system, lead on to optimum, and refine the judgement on which the final decisions are to be made.

In this study a first attempt has been made to decompose the Indus system into subsystems for analytical purposes. Some suggestions have also been made regarding the system re-integration in certain respects.

For the purposes of this study, the author has selected a typical subsystem to form a physical model and develop an optimization procedure for it. For the selection of this model the following actions are required.

a. Select a model area.

b. Determine the surface hydrology for the model area.

c. Specify the surface storage facilities for the model area and determine its characteristics.

d. Determine the subsurface hydrology and the aquifer characteristics for the model area.

e. Select a cropping pattern for the model area.

f. Determine the monthly irrigation water demands for the model area.

g. Other considerations.

These steps are briefly explained as follows.

2. The Model Area: The area under the Marala-Ravi link canal system in the Rechna Doab (M-R link internal) has been selected for the physical model. It comprises 164,000 acres of cultural commanded area. The reasons for this choice are:

a. The selected area is underlain by fresh water aquifer throughout; no saline or intermediate water quality aquifer is present in this area. This enables one to exclude the water quality parameter from the optimization model. Inclusion of this parameter in the model is suggested as the subject of future research.

b. The optimization model for a single canal system is more versatile and of greater practical value. It can be used to analyze any other canal system of the Indus Basin Irrigation System, directly or after extensions by feeding the input data for that canal system. This is possible because the problems, parameters, and variables for all canal systems in the Indus Basin Plains are more or less similar. A canal system is a basic unit of the Indus Basin irrigation system.

c. The results from this model can be used in a higher level model for optimizing the overall system. For example, a procedure for optimum allocation of surface water resources to various canal systems can be developed on the basis of these results.

3. Surface Hydrology for the Model Area: The various canal command areas in the Indus Basin Irrigation System receive their surface water supplies from the common surface water resources of the region. To uncouple the model area from the other areas in respect of surface hydrology it is essential to

determine the share of the model area in the common surface water resources. This will make the model area a hydrologically independent unit with its own well defined surface water hydrology. Doing this involves the problem of optimum allocation of the available surface water resources to various canal systems with due regard to the water rights of the various areas. The following points are pertinent in this connection.

a. In contrast to the USA, there are no established water rights for the farmers in West Pakistan. All water rights are vested in the government to facilitate the operation, expansion and development of the irrigation system. There are positive and negative points in this type of control. For example, it provides a high degree of flexibility in the system operation but makes the farmers completely dependent upon the government officials.

b. Historically, the Indus Basin Irrigation System has received water on the basis of the run-of-the-river supplies through canals, the inflow to which is controlled at their offtake points by diversion structures on the rivers, called headworks. The water diversion into the canals, in any month, is limited by the least of the following:

   (1) the flows in the river;
   (2) the canal capacity, or
   (3) the water demand.

   The water shortage during sowing and maturing periods limits the area sown to crops in a given season, and therefore limits the water demand, even during high flow periods when more water could physically be supplied. At some other time periods, when field needs for water and river flows are high the existing canal capacities may be a limiting factor.

c. The Indus Basin hydrology is characterized by monsoon climate with high river flows during summer and a general water scarcity during winter months. The two major reservoirs, Mangla and Tarbela constructed recently provide some re-regulation in river

flows but the run-of-the-river water supply characteristics of the irrigation system still predominates. Since different distribution rules apply to scarcity and abundance, different allocation rules are needed for months of low and high river flows.

d. Looking for guidelines for allocating the available monthly surface water supplies to various areas, it may be noted that an agreement exists between the upper and the lower Indus areas on the division of the Indus System river flows. The agreement is called the Sind-Punjab agreement of 1945. In addition, there are some broad rules which govern the priority of receiving the available river flows by various canal systems. Both the Sind-Punjab agreement and the priority rules for the various canal systems are of particular importance during the periods of water scarcity. These rules, however, operate in a complicated way and most of them are taken as a flexible guide rather than a law. Deciphering an allocation policy on the basis of the said agreement and rules is in itself a major project, if it can at all be accomplished. To overcome this difficulty, the author has assumed that the historical water uses or diversions into various canal systems reflect the said agreement and the priority rules, and they represent, at least in broad terms, the recognized allocation policy or agreed water rights of various areas.

Based on the foregoing observations, the following surface water allocation rules have been adopted.

a. In months of low river flows, the total river flows in the Indus system shall be allocated to various areas in proportion to their average historical uses.

b. In months of high river flows, each area shall have a water allocation equal to its average historical use plus a percentage of the surplus water available over and above the historical use. For the purposes of this study, this percentage is arbitrarily assumed as 1%. In a later computer run it was reduced to 0.5%.

Using these rules and the 42 years of monthly river flow data for the period 1922 to 1963, a deterministic surface hydrology for the model area has been determined for use in this study.

The water allocation so obtained is not optimal but is considered reasonable for the purposes of this study. An optimal water allocation to various canal systems requires further research to cover the entire system. A procedure for this optimum water allocation has been suggested in the main report.

4. The Surface Storage Facilities: The surface storage facilities on the Indus System, present or future, have to be shared by many canal systems. Since for analytical purposes the model area should have its own storage facility, it is assumed that a portion of the surface storage can be set apart for this model area in a common surface reservoir, and appropriate cost of it can be charged to the model area.

This provides a conceptually independent surface storage facility for the model area. Determining the optimum size of this storage facility is a decision variable in this study. Doing this for all canal systems will provide data from which the optimum size of the total surface reservoir capacity to be provided can be determined.

5. Aquifer Reservoir: The aquifer extends under the entire model area and is more than 1000 feet in depth. The minimum allowable ground water depth is taken as 10 feet and the maximum 90 feet below the ground surface. It is assumed to have an average storage coefficient of 0.2. The ground water is classified as fresh, with less than 1000 ppm total dissolved solids.

The recharge to this aquifer reservoir will take place from:

a. natural resources (rainfall);

b. the irrigation system (canal network, water courses, fields); or

c. diversion of additional water from the river into the irrigation system for recharge by over-irrigation or flooding of the shallow area.

No special recharge facility has been provided and therefore no specific costs have been assigned to recharge. Providing specific recharge facilities in the model area and other areas, would require that the recharge costs be taken into account. It is recommended that a detailed investigation for this purpose be carried out. In fact, the entire recharge problem requires a comprehensive investigation program. This will be explained in a separate paper.

For the present study, a recharge criteria based on the previous studies has been established as in Table 1.

Table 1. Irrigation System Losses and Ground Water Recharge Criteria Adopted for this Study.

System portion	Water losses	Recharge
1. Canal system up to water course head	28% of water supplied at canal head works	80% of losses
2. Water Courses	10% of water supplied at water course head	50% of losses
3. Farms	30% of water delivered at field or 27% of the water delivered at water course head	67% of losses

The total recharge from items 1 through 3 above, works out to be 54% of the canal water supplied at the water course head. The tubewell water is assumed to be supplied at the water course head, and using the cirteria in Table 1, 22% of the aquifer water pumped for irrigation goes back to the aquifer reservoir as recharge. The average recharge from rainfall is taken to be 4.5 inches per annum. The actual recharge from rainfall will vary stochastically with time. Taking the average, simplifies computations without materially affecting the results. Recharge from the rivers is taken as zero for the model area. Also, subsurface flow into the area from adjoining areas is taken as equal to the subsurface flow out of the area, as a first approximation.

6. The Cropping Pattern: The amount of irrigation water required for a given area depends upon the cropping pattern which specifies the type and intensity of the crops to be grown. The decision on cropping pattern, in turn, depends on the physiography of the area (soil types, climate, etc.), on the one hand, and socio-political and economic considerations on the other. Water supply acts as an overriding constraint on the available choices. One faces here a problem of circular relationships. The water demand depends on cropping pattern and cropping pattern on water supply; and in water scarcity areas, the supply and demand have got to be balanced. The problem is further complicated by socio-political considerations and the overall economic perspective of the country. Independent and comprehensive studies on cropping pattern for West Pakistan have been made by Harza (1963), T & K (1967) and IACA (1966). They have recommended somewhat different cropping patterns. The cropping pattern suggested by IACA (1966) has been adopted for this study to compute the monthly irrigation water demands for the model area. Further research is, however, necessary to determine optimum cropping pattern.

7. The Monthly Irrigation Water Demand: The computations for optimum monthly irrigation water demands for a given cropping pattern depend on a number of factors such as climate, soils, seed types, fertilizers, and agricultural practices. Determination of optimum timing of irrigation and critical growth periods of the crops are also important factors which need future research. For this study the author has used a procedure suggested by IACA (1966) for computing the irrigation water requirements for West Pakistan. The monthly irrigation water demands computed at water course head vary from month to month, but the requirements for any month are taken as invariant over years for the purpose of system planning and design.

8. Other Considerations: In West Pakistan all large scale surface storage projects must be multipurpose in scope to be economically feasible. Irrigation and power are the major functions which have to bear the cost of the surface storages. In this study a portion of the surface storage costs

has been allocated to power as per Lieftinck, et. al. (1969). Charging the remaining costs to irrigation, a cost function for surface storage has been developed for irrigation alone. In this way power function of the multipurpose surface storage project has been uncoupled from the irrigation function. The power function is then excluded from the optimization model. Future research is recommended to extend the present model to include the optimization for power.

9. Recapitulation: By a step by step decomposition and parameterizing procedure, the author has developed a physical model for optimizing the conjunctive use of surface and ground water resources of a subsystem of the Indus Basin in Pakistan. A schematic diagram of this model is shown in Fig. 2.

a. Components of the Physical Model - The major components of the model are:

(1) a model area A1 comprising 164,000 acres under Marala-Ravi link canal in the Rechna Doab;

(2) a river with deterministic hydrology;

(3) a surface storage of capacity TQ to be determined;

(4) a canal system with conveyance capacity TC to be determined;

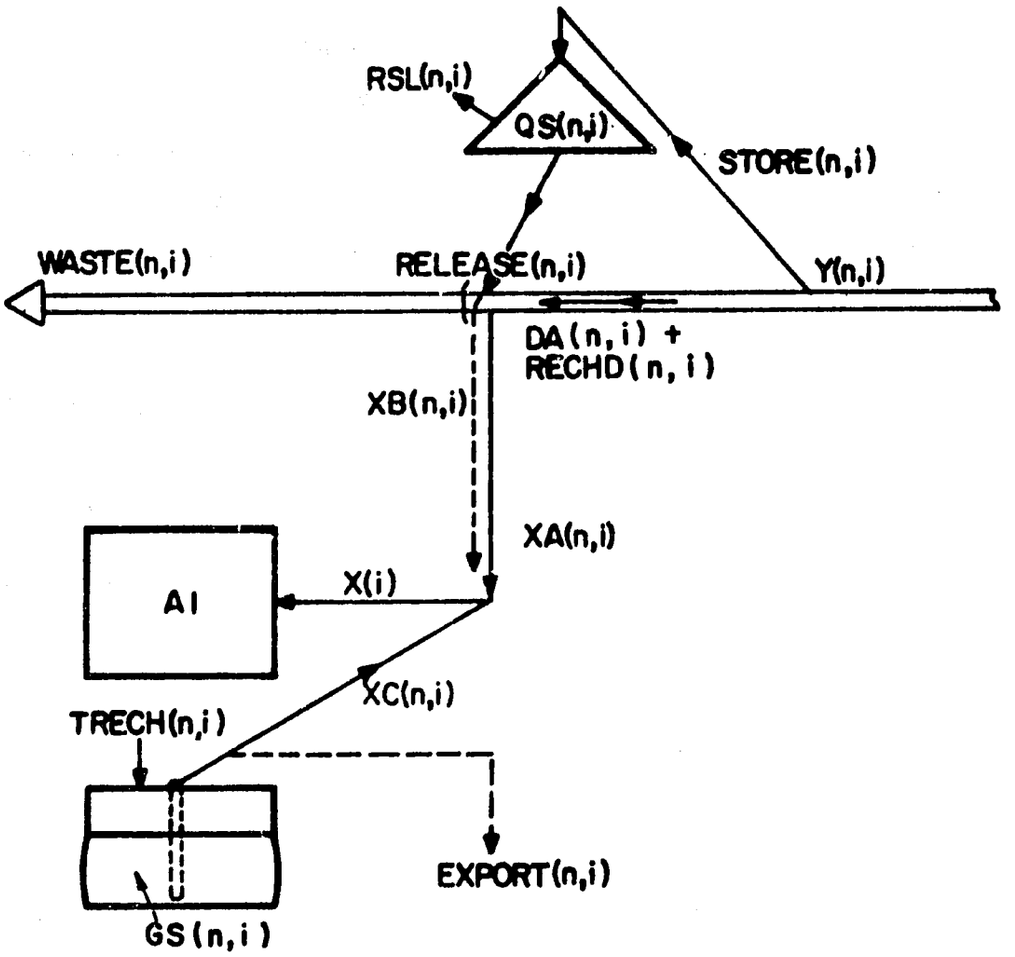
(5) an aquifer reservoir with known characteristics, the required pumping capacity Tp is to be determined;

(6) the monthly irrigation water demands for the model area, computed from a given cropping pattern which will be met in full except for occasional shortages of 10%; and

(7) an export component, which provides for sale of pumped water from aquifer storage to other areas at dump price.

b. Assumptions - The following assumptions are made in formulating the physical model described in the foregoing section:

(1) The surface flows Y(n, i), allocated to the model area are available for its exclusive use.



(See page 21 for definitions of symbols)

Fig. 2. - The Subsystem Model

(2) A conceptual surface storage of desired size is available for exclusive use of the model area. This can be done by reserving the required storage space in common surface reservoirs.

(3) The subsurface flow into the model area equals the subsurface outflow from the area. The aquifer reservoir can thus be taken independent from the surrounding areas.

(4) Cropping pattern is taken as given. This is based on earlier studies made by IACA (1966).

(5) The method used by IACA (1966) to compute monthly irrigation water requirements is adopted to compute the monthly water demand for the model area. The monthly irrigation water demands, so computed, are taken as given input data.

(6) The model area being underlain entirely by fresh water aquifer the water quality parameter is not included in the model.

(7) The optimization for the hydropower is not included in the model. The hydropower function of surface storage projects has been uncoupled from the irrigation function by allocating cost of the surface reservoir to the two functions.

Notation: The symbols used in Fig. 2 are:

A_1 = Irrigation area

i = Index for month; i = 1, 2.....12

n = Index for year; n = 1, 2, ...N

H = planning horizons in years, 42 years in this study

$X_{(i)}$ = Irrigation water demand for month i, at water course head (WEH)

$XA_{(n,i)}$=that part of $X_{(i)}$ which is met from direct river water diversion into the irrigation canal system

$XB_{(n,i)}$=that part of $X_{(i)}$ which is met from releases from the surface reservoir

$XC_{(n,i)}$=that part of $X_{(i)}$ which is met from releases from the aquifer reservoir or ground water pumping

$Y_{(n,i)}$ = the monthly river flows available for use by the model area A_1

$DA_{(n,i)}$=the monthly river diversions into the canal system for irrigation at canal head

$STORE_{(n,i)}$= the monthly river water stored in the surface reservoir

$RECHD_{(n,i)}$= the additional river water diverted into the irrigation canal system during month i of year n

$WASTE_{(n,i)}$= water let down the river unused during month i for year n

$RELEASE_{(n,i)}$= the monthly water releases from the surface reservoir

$RSL_{(n,i)}$ = the monthly surface reservoir losses

$EXPORT_{(n,i)}$ = the amount of ground water pumped for export from the model area to other areas during month i of year n. This may be for drainage, long term salt balance or for irrigation water supply to other areas from the fresh water aquifer reservoir.

TC = the capacity of the irrigation canal system at canal headwork in Millions of Acre Feet/month

TQ = the capacity of the surface reservoir in MAF

$QS_{(n,i)}$= the amount of water in the surface reservoir at the beginning of month i of year n

TC = the installed ground water pumping capacity in MAF/month

TC = The aquifer reservoir capacity between the maximum and minimum allowable ground water levels

$GS_{(n,i)}$ = the state or the amount of water in the aquifer reservoir at the beginning of month i of year n

$TRECH_{(n,i)}$ = the monthly ground water recharge

The Objective

The objective of optimizing the conjunctive use of surface and ground water resources to optimize the net benefits from the irrigation area defined as follows:

Net benefits = benefits from the agricultural produce – the cost of irrigation water supply.

The benefits from the agricultural produce in this definition include the farm costs as negative benefits.

For given monthly irrigation supply (demand), the benefit from the agricultural produce can be maximized, independent of the cost of the irrigation water supply. Assuming this is done, maximizing net benefits will require minimization of the cost of irrigation water supply. Although for the overall system optimization, one needs to both maximize the benefits and minimize the costs, the foregoing stipulation enables consideration of the benefits and costs separately.

This study is aimed at minimizing the cost of given monthly irrigation water supply. The problem of maximizing the corresponding agricultural benefits is suggested for future research. When this is done, it will give one point on the production function, or a curve which defines the optimum net benefits reflecting economically most efficient use of inputs and the outputs involved in an irrigation agriculture system. However, once the respective optimization models are available, the computer can define the complete production function or a curve for various levels of irrigation water supply developed according to a given demand pattern (see Fig. 3). Changing the demand pattern by changing the cropping pattern or water use practices, will result in another curve for the production function. Thus a family of curves for the production function for various types of stipulations can be obtained.

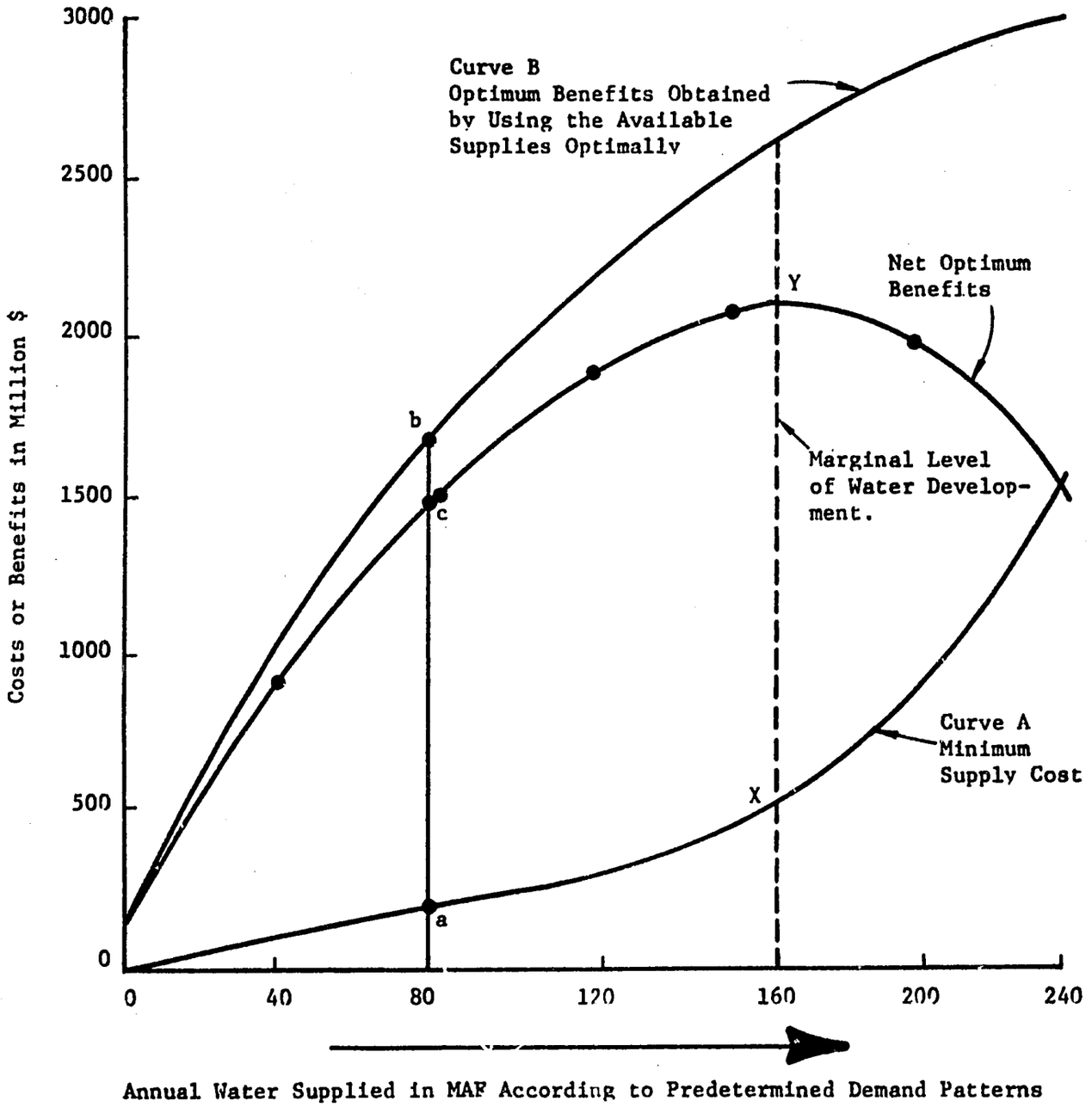


FIG. 3. UNCOUPLING OF COST FROM BENEFITS

Note: The curves are hypothetical. These are designed to show how the optimization problem relating to conjunctive use of surface and groundwater can be decomposed into two problems:
(1) Minimizing the supply costs
(2) Maximizing the use benefits.

These curves will provide the necessary data for the overall optimization of the system. This is, however, a visualization, which requires future research.

In this study attention has been focussed on minimizing the cost of meeting the given monthly irrigation demand. Even this problem can be decomposed into two subproblems. One relates to the short run objective function, or what the engineers would like to call operation problem. In this problem, the objective is to optimally operate the system as it exists, without providing or stipulating any additional physical facility. Availability of a short run objective function optimizing model is most useful in making day to day operations decisions, using the available information from the past records and the new information on the system as it becomes available. Since the system optimization in this case adapts to the new information as one marches into the future, the optimization process is also called adaptive control process.

The other problem related to the minimization of the cost of irrigation water supply is the long run objective function or what the engineers call the design problem. It visualizes adding new physical facilities to the existing system, including expansion of the facilities that may be already available. For an efficient design, it is essential that not only the combination of the various physical facilities give minimum additional capital cost, but also the predictable operation and maintenance costs of the system over the planning horizon or the project life are minimized.

This study concentrates on the design problem. The design problem involves comparing the costs of alternative designs, or the possible combinations for design parameters;

TC = the canal capacity

TP = the pumping capacity

TQ = the surface reservoir capacity

and choosing the least cost alternative or combination of the said design parameters, that meets the monthly water demand within applicable constraints.

The Mathematical Model

The next step is to transcribe the physical model given in Fig. 2 and the foregoing objective into a set of mathematical relationships which define:

1. A ranking function or objective function which evaluates the various design alternatives in terms of the given objective. In this specific case the objective function computes the capital and operation and maintenance cost for a given design alternative for comparison with the costs of other alternatives, similarly obtained.
2. A set of constraint equations which limits the choice of the design alternative and its operation within some predetermined feasible region or policy space. Such constraints are imposed on the system by a variety of physical, social, legal and political factors. For example the canal water supply cannot exceed the canal capacity, the river water diversion for ground water recharge cannot be allowed to exceed a limit beyond which the irrigation area will be flooded to cause flood damages.

The strategy and the procedure adopted for mathematical solution of the problems are given in the following. Mathematical details have been omitted in this description.

1. A Strategy for Solution: In general, more than one strategy can be applied to solve any engineering problem. Selection of the "best" strategy depends on the problem and theoretical and computational tools available for solving it. The strategy for solving the present problem is based on the insights provided by previous research, and intuitive judgement. According to this strategy, a set of discrete values for each of the design variables TC, TP and TQ, over a range of these parameters is chosen. Thus:

$$TC = TC_1,\ TC_2,\ TC_3\ .\ .\ .\ TC_\ell$$
$$TP = TP_1,\ TP_2,\ TP_3\ .\ .\ .\ TP_m$$
$$TQ = TQ_1,\ TQ_2,\ TQ_3\ .\ .\ .\ TQ_n$$

A design alternative is then defined as the set:

$$(TC_i,\ TP_j,\ TQ_k)$$

with $i = 1, 2, 3, \ldots \ell$

$j = 1, 2, 3, \ldots m$

$k = 1, 2, 3, \ldots n$

This gives rise to $\ell . m . n$ design alternatives. The procedure is to take the first design in the matrix $(TC_i,\ TP_i,\ TQ_1)$ and determine the optimum operation policy for it over the planning horizon. Knowing the design size and the optimum operation policy, it is possible to compute the total capital and Operation and Maintenance (O & M) costs for this design alternative. Then the next design $(TC_1,\ TP_1,\ TQ_2)$ is selected and process repeated; and so on. The design alternative which results in the least capital and O & M costs over the planning horizon is the desired optimum design.

In the discretization process, it is generally wiser to start with a coarse grid system with a wide enough range of the design variables to cover all possibilities. Results obtained from this preliminary study will enable one to narrow down the range within which a finer grid system can be adopted for more accurate results.

The final grid system adopted in this study is:

TC = 52, 60, 65, 70, 75, 80, 90, 100, 110, 120, 130, 140 KAF/month

TP = 0, 20, 40, 50, 55, 60, 65, 70, 75, 80, 100, 120 KAF/month

TQ = 0, 20, 50, 60, 80, 100, 120, 140 KAF/month, (1 KAF = 1000 Acre Feet)

In all 12 values for canal capacity TC, 12 values for ground water pumping capacity TP, and 8 values of surface reservoir capacity TQ are stipulated. This gives rise to 12 x 12 x 8 = 1152 design alternatives. The various values of the design parameters form input data in the computer program. Additional design alternatives could be stipulated if desirable. To avoid excessive computer time that would be required to test all the design alternatives, a "systematic search algorithm" has been developed for the purpose of this study. This reduces the design alternatives to be actually tested to about 5% of the total stipulated alternatives.

More than one feasibility test has been built in the computer program so that many of the design alternatives under test are dropped, after only partial processing, as soon as they fail to meet a required feasibility test. The term feasibility here refers to the physical feasibility and not the economic or financial feasibility, which can be determined after the least cost physical alternative design is known.

2. A Solution Procedure: The mathematical formulation of the problem of this study gives rise to a highly complex nonlinear problem. Solution of this problem by direct application of one of the several available optimization techniques (linear, nonlinear, dynamic and others) may give some type of mathematically elegant procedure, but this approach has not been adopted here. Instead, advantage is taken of an empirical scientific approach and using the physical insights, the problem has been further decomposed and finally reformulated into a two level problem. The computer program written to solve this two level problem uses a combination of a parametric and one dimensional dynamic programming optimization technique as explained in the following.

a. The upper level or what one can call a master or controlling program reads the input data; uses a subroutine to compute the surface hydrology for the model area; generates the design alternatives and selects the successive design alternatives to be tested using a systematic search algorithm; passes down the information regarding a selected design to the lower level problems and obtains back the monthly optimum operation policy from them; and using appropriate subroutines computes the annual cost of the given design alternative for comparing with the costs similarly obtained for other design alternatives. A subroutine enables export of water from the model area to other areas under, if desired. The master program also performs the various types of bookkeeping.

b. At the lower level, there are two one dimensional dynamic programs which allow determination of optimal monthly operation policy for high river flow season and the low river flow season respectively for each year. It is stipulated in the problem that no multiyear carryover surface storage will be provided in the system. This enables the system operation to perform independently for each year.

For further details, the main dissertation report may be referred to.

The Results

For the physical model presented in Fig. 2, the optimal design is given to be:

Canal capacity TC = 80 KAF/month
Ground water pumping capacity TP = 55 KAF/month
Surface reservoir capacity TQ = 0.0 KAF/month

This is assuming no export of the ground water from the model area for use by the other areas.

Another computer run was made with the stipulation that the spare ground water pumping capacity during the low river flow season will be used to export ground water from the model area to other areas for irrigation. Without going into the details of such a transfer, a credit of $2.00 per acre ft. pumped for export is given to the model area. The optimum design then is:

Canal capacity TC = 140.00 KAF/month
Pumping capacity TP = 50.00 KAF/month
Reservoir capacity TQ = 0.0 KAF.

It is thus indicated that under the stipulation made for arriving at the physical model for this study, the optimum design does not include any surface reservoir. Optimizing power generation may alter this result but the study still emphasizes the maximum use of aquifer reservoir. It also emphasizes the importance of further research on conjunctive use.

For more details on the results of this study, reference is invited to the main dissertation report.

Conclusions and Recommendations

This research has attempted to provide a working mathematical tool for analyzing and optimizing the conjunctive use of surface and ground water resources of the Indus Basin in Pakistan. The study, however, is limited in scope as it deals with only a small subset of the whole system. Furthermore, the Indus Basin irrigation system is complex and interconnected. Setting apart a small subset of it from the rest of the system, to formulate a physical model, involves a system decomposition process. To accomplish this, certain assumptions have been made, which need further research to determine the possible errors involved in decomposing and subsequent reintegration of the results for the whole system.

In spite of these limitations, the research effort has brought out some points which are of value for more effective water resources development and management in Pakistan. The research also provides a preliminary framework for carrying out the future research on the optimum conjunctive use of the Indus Basin water resources. This study, in fact, has been the first attempt in this connection.

The main interest of this research has been centered in formulating an optimizing model and obtaining a solution for it. Accomplishing this is the major achievement of this study. The relevant results are given under the foregoing section. An attempt is made in this section to draw some broad conclusions and make some equally broad recommendations. These contain the author's opinions and need further research before they are to be finally accepted.

1. The optimum design obtained for the model area of this study does not include the surface storage. The aquifer reservoir underlying the model area can meet its seasonal as well as multiyear carryover needs at a cheaper cost as compared to the surface storage (Chaudhry 1973).

Since, on the average, the same recharge criteria and the storage coefficient used for the model area are reasonable estimates for all fresh aquifer areas in the Indus Basin (Chaudhry 1973, pp 54-62), the author is of the opinion that the foregoing results for the model area can be considered valid for other fresh water areas as well. This is, of course, subject to limitations mentioned earlier in this chapter and the local variations of the aquifer characteristics.

The use of aquifer reservoirs as functional reservoirs has the following additional advantages.

a. The heavy evaporation losses that occur from the surface reservoirs are avoided, particularly when they are used for multiyear carryover storage.

b. The aquifer reservoirs enable recycling of irrigation water and thus increase the net utilizable water resources.

c. There is a time lag between the water releases from the surface reservoir and its availability at the points of use. The withdrawals (pumping) from the aquifer reservoir are generally made more or less at the point of water use. The problem of time lag is, therefore, not involved in this case. In other words, it means that the water supply from the aquifer reservoir is more flexible as compared to that from the surface storage.

2. In addition to serving their overlying areas, fresh water aquifers may also store water for adjoining saline aquifer areas at cheaper cost as compared to the surface storage facilities. This statement is again based on the extension of the results for the model area to other fresh water areas for the same reasons as in 1. The limitations mentioned in 1 also apply in this case.

3. Defining the storage efficiency as the storage water supplied at the water course head expressed as a percentage of the river water diverted to the storage reservoir, it is observed that the storage efficiency for surface reservoirs like Tarbela is about 57% (Lieftinck, et al 1969). The storage

efficiency for aquifer reservoirs, without any specific recharge facility is about 54%. Building specific recharge facilities wherever possible, will increase the recharge efficiency and therefore the storage efficiency of the aquifer reservoirs. It thus appears that efficiency of storing and using river flows is about the same in cases of both surface storage and underground storage. Underground storage has the additional advantage that a major percentage of water can be used for irrigation before it gets stored underground. For multiyear carryover storage, the efficiency of the aquifer reservoir may be even greater than the surface reservoir because of greater evaporation losses from the latter. The recharge to the aquifer, however, is a much slower process as compared to the impoundment of the surface storage. This places a limitation on the use of aquifer reservoirs and needs to be investigated in detail.

4. Although the conclusion is not final, there is a reasonable indication that as far as possible the fresh water from the river should be supplied to the fresh water aquifer areas. Fifty-four percent of this water will become available in the underground reservoir with only a slight decrease in quality for reuse in the same area or export to other areas. This has the following advantages:

a. When the first use of the river water is on the fresh aquifer areas, 54% of the water so used is recharged into the aquifer reservoir. If this recharged water is pumped for use in the same areas, 22% of it is recharged back into the aquifer reservoir and so on. This recycling of the irrigation water by effective use of fresh water aquifers results in about 70% increase in the useable water resources.

b. When the first use of the river water is on the fresh aquifer areas and the recharge water from such areas is pumped for use in saline aquifer areas, there is an increase of 54% in the useable water resources, thus used, because of recycling afforded by underground reservoir. No such recycling advantage is available

when the river water is used directly on areas with saline ground water.[1] On the other hand, the recharge water in such areas must be drained away at a cost because it contains too much salt to be useable for irrigation.

On the basis of reasons given in 4 a and b, it can be argued that the canal system should be left leaky or unlined in the freshwater aquifer areas and be lined in the brackish water areas. Also the nonsaline areas may be sown with crops requiring and withstanding higher water application (rice for example) while saline areas may grow crops with less water requirements (cotton for instance) subject, of course, to the water quality considerations.

c. From the viewpoint of long term salt balance in fresh water areas, the policy recommended in 4a is eminently suitable. At least a part of underground water from fresh-water areas needs to be exported to other areas for this purpose. If the water from a fresh aquifer is used in the overlying area over and over again without exporting any part of it, it will eventually become undesirably concentrated with salts brought by the canal water into the area Use of slightly saline water on soils overlying aquifers bearing saline waters does not pose the additional problem because the saline subsurface waters from these areas must be disposed of anyway.

5. By effective use of the fresh aquifer reservoir, some 4 MAF[2] of naturally occurring recharge from rainfall can be made available as valuable storage water.

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[1] There is a possibility of creating fresh water mounds over the saline water or reclaiming the saline aquifers by flushing, in at least some cases. Future research is required on this issue. Assuming that the possibility is economically feasible, the conclusions reported here may have to be adjusted to the new findings, in certain respects.

[2] Harza (1963) has estimated a weighted average recharge of 2.3" per annum for the entire Punjab area. Using the same average for the entire 19 million acres of useable aquifer area under the Indus system canals, the annual recharge works out to be about 4 MAF. Under conditions of deep or excessively high ground water tables and sparse cultivation most of it will be lost to evaporation. With proper aquifer management and intensive cultivation most of it can be conserved for useful purposes.

6. The foregoing conclusions are based on the potentialities of the conjunctive use and the possibilities of replacing a part of surface storage by aquifer storage. Their socio-economic feasibility is subject to further research for the entire Pakistan area. Also this research is limited to only a small part of a large interconnected irrigation system. However, if the conclusions given here are upheld by further research, the requirement of surface storage for irrigation will be considerably reduced.

7. Continued research on conjunctive use of the surface and ground water resources of the Indus Basin is important for agricultural development in Pakistan. The author is of the opinion that:

a. The existing water supply to the irrigation fields can be increased considerably and most economically by optimal conjunctive use of surface and ground water resources. This will be the most welcome relief to the Pakistani farmers whose crops are generally short of water under the existing conditions.

b. The conjunctive use of surface and ground water resources can alleviate the uncertainties of water supply for irrigation. The system could then be managed as "supply-on-demand" system as against the present "use-when-available" system. The latter, of course, is generally less efficient in producing crops per unit of water.

c. With the capability of the system to supply the irrigation water on demand, the other "on farm" research will become more meaningful than it can be under the present constraints of shortage and uncertainty of water. Adequate and assured water supply, which in the authors opinion, is possible by the conjunctive use of surface and ground water resources, will assure adequate returns from the investments in fertilizers, better seeds, better agricultural implements and other farm inputs. On the other hand, investments in these inputs under the present conditions of uncertain and scarce water supply, as stated earlier, can easily

lead the farmer, living on subsistence level, to a situation of "the gamblers ruin problem". The farmers are, therefore, very naturally inhibited in making the much desired investments in these inputs.

d. Studies show that present crop yield in Pakistan is about 1/3 of the yields obtained in other countries (see Table 2).

Table 2. Comparison of Agricultural Productivity in Selected Countries (from Revelle, 1964)

YIELD IN POUNDS PER ACRE						
Crop	Pakistan	Egypt	Japan	U.S.A.	W. Europe	E. Europe
Cleaned Rice	820	2,305	2,765	2,200	3,015	1,540
Wheat	695	2,090	2,005	1,465	1,740	1,345
Corn	945	1,850	1.955	2,890	2,110	1,600
Cotton Lint	185	525	--	980	--	255
Sugar Cane Raw Sugar	2,580	---	--	4,340	--	--

This indicates that if water supply situation is corrected, the crop yield may be increased at least three-fold. Attaining this would require other inputs but to realize the full potential of these inputs, it is important that the water supply constraints are overcome. Furthermore, by improving the irrigation water supply through "conjunctive use", the irrigation intensity can be increased from a present value of about 80% per annum to about 150% per annum or more, thus increasing the area under crops each season.

Combining these two factors, the crop yield in Pakistan can potentially be increased 5 to 6 times. More research is needed to ascertain the attainability of this potential.

9. In conclusion, it may be stated that in Pakistan there are more than one alternative approaches to the future development of the water resources. One alternative is to construct surface storage to conserve the surplus water during the high flow periods for use during the low flow periods, using the ground water as supplemental supplies. Another alternative is to use the ground water aquifer as a functional reservoir to the maximum possible extent and use the surface storage supplies as supplemental water.

Between and within the two extremes, there are many alternative combinations. The objective of the conjunctive use studies is to determine the best alternative subject to the applicable constraints. This is required both for the design of the system for future development and operation of the system as it exists today or as it may exist in the future.

The first step to do this is to prepare optimizing models of various types for specific conditions of Pakistan. This can best be done at the university level, where the necessary expertise and research facilities exist for this purpose. To facilitate the use of these optimizing models, the available information on the Indus system will be used and analyzed, but the results obtained will be used only as a guide and not for actual formulation of the development schemes. The model prepared in this research is the first of this type and the results thereof should be used in the said context.

The actual planning and design of the system, which require major investments in time, money and information, can best be done by planning and design agencies, with which the university can collaborate if necessary. The optimizing model prepared at the university level will greatly facilitate the work at this stage. They will also help to identify the design and operation alternatives which, otherwise, may not be visible.

In the authors opinion, there is an urgency to continue and accelerate the research on optimizing the conjunctive use. Large scale investments are being continually made on the design and construction of water resources works. Most of these investments are irreversible. These investments can be more productive, if they have the benefit of the modern tool of systems analysis and optimization. A case in point is the $6 million pilot scheme to line the water courses in the Punjab area, (the Pakistan Times, dated January 1973). The present study raises the question of whether it is more economical to leave the water courses in the fresh aquifer areas unlined as a facility for aquifer recharge, and recover the seepage water from the aquifer by installing tubewells, when it is most needed. This concept at least merits investigation. This, in turn, is closely linked with the optimum conjunctive use of the water resources of the system.

Quittance

The investments in the water resources system are mostly irreversible. Decisions such as modification or lining of the water courses, installation of new tubewells and others can be misleading if taken without looking at the water resources system as a whole. Therefore, even if the actual physical actions under the water management research project are limited to water courses and the irrigation fields, a coordinated study should be encouraged to develop optimizing tools for theoretical analysis of the whole Indus Basin water resources system. This will illuminate the path for more effective "on farm" research than is otherwise possible.

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