Waterlogging and Salinity in the Indus Plain : Some Basic Considerations

by

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INTRODUCTION

It takes more than ordinary presumption for a group of strangers to recommend changes in the efforts of a great nation to contend with a problem that goes to the very roots of its social structure and its livelihood. Yet we did just that in our *Report on Land and Water Development in the Indus Plain*[1]. We hoped our recommendations would be considered sympathetically and debated fully, that our sound suggestions would be adopted and our unsound ones forgiven. All this has been granted us, and more.

The months since the Panel's report was prepared have been eventful for the economic development of West Pakistan. It is hard to cast our minds back to the gloom that filled the atmosphere when the Panel was convened. Food production had been stagnant for the past several years, *sem* and *thur* were spreading through the most productive portions of the Plain, expensive efforts to control these twin menaces had been baffled. WAPDA knew, of course, that in principle tubewells could do the job, but there were more failures to report than successes. The yields of major crops were about what they had been five years before, and population growth was outstripping production.

is complacency—the premature conclusion that the programs already undertaken will suffice. They will not. The first positive steps have brought dramatic results because there was so much room for improvement in the cultivation of the Indus Plain. But fundamental shortcomings persist. There is still much hard work to be done. Just as our first message was one of hopefulness in a time of gloom, so now we want to offer some sober appraisals in a time of confidence.

One of the central themes of our report was *interaction*. We found that the agriculture of West Pakistan was beset by numerous deficiencies. Efforts to correct any one of these could have only limited success, because the uncorrected shortcomings would still set a low ceiling to agricultural productivity. On the other hand, simultaneous measures to provide additional irrigation water; reclaim deteriorated land; supply chemical fertilizers, plant protection, and improved seeds; instruct farmers in the proper use of these materials and in modern agricultural methods; increase the ease and rapidity of loans to farmers; and improve marketing procedures and facilities—all concentrated on the same area—would be mutually supporting and would yield far greater increases in output than the same efforts scattered over different places. For these reasons we recommended the formation of the Land and Water Development Board and of local administrations, each responsible to the Board for supervising physical improvements and a number of agricultural programs in a single compact area. Because Pakistan has a limited supply of administrative resources, we recommended the strategy of starting project areas in succession, with development of no more than about a million acres being undertaken in any one year. We still adhere, in the main, to this broad concept. But now it appears that we overestimated some of the difficulties. Since the publication of our report, the farmers of West Pakistan have demonstrated more initiative and more willingness to adopt modern agricultural practices than we anticipated. This is indicated by the rapid spread of private tubewells—about 6,500 a year—and by the eager adoption of chemical fertilizers—usage increasing at about 20 per cent per year recently. Furthermore, it seems evident that the distribution of fertilizer, seeds, and other materials of agriculture can be accomplished efficiently through ordinary commercial channels. Thus, the agricultural administration can concentrate on providing water, agricultural advisory services, credit, and storage and marketing facilities, leaving the problems of distribution of agricultural materials and even some of the work of supplying irrigation water to private initiative. The resulting economies in the utilization of scarce administrative and technical manpower may permit a considerable acceleration of the program.

for expenditure that the Plan was most successful, though support fo that statement is beyond the scope of the present paper. A review of Se Plan tax proposals and their implementation will illustrate the general succe ting policies adopted.

The *Second Plan* advocated "a greater use of taxes and subsi a desirable allocation of resources instead of relying on a multip controls..." [11, p. 49]. In particular it argued strongly for an import to eliminate the windfall gains to import licensees and eventually system itself [11, pp. 50-51]. While the aim was not achieved, import

TABLE VI

GROWTH OF TAX REVENUE : PROJECTED AND ACTU

	Second Plan projections 1964/65 at 1959/60 rates	1964/65 estimates from Third Plan	R
Income and corporation tax	400	633	
Land revenue	320	307	
Customs	550	1080	
Excises	390	849	
Sales taxes	390	750	
Miscellaneous taxes	220	362	
Total	2270	3981	
Additional taxation	1750	—	
Total taxation	4020	3981	

Sources: *Second Plan* projections: 1964/65 at 1959/60 rates from *Second Plan* [11, p. 5 tional taxation from *Revised Estimates* [11, p. 23]. 1964/65 estimates (at 196 including additional taxation) from *Third Plan* [16, p. 67].

taken. Table VII shows the average rate of taxes (import duty plus sales t imports at the beginning and at the end of the Plan period. Notable inc were made in the 1960/61 budget and smaller changes were made thro the Plan period, including, finally, a "regulatory duty" on items inclu the new Free List of license-free imports in June 1964. In an important however, the increased reliance on the market for determining import c tion as due not to increased duties of a regulatory nature, but to substantial incre in the balance of payments deficit on goods and services account whi nanced by increased aid. It was primarily the increased availability c change that made the increased market dependence work; not the uty structure, even though substantial changes were made in the

recommended lowering the rate of export duties on cotton and, ent, on jute. These recommendations were adopted in successsive adhu's summary tables [20; 21] show. Excise duties were also in- ordance with the Second Plan objectives, and, in the last budgets

TABLE VII

ES OF TAX ON IMPORTED GOODS BY TYPE OF COMMODITY

(Percentage of c. & f. price)

	1959/60	1960/61	1964/65
goods			
sentials	35	55	56
mi luxuries	54	111	118
Luxuries	99	140	144
erials for consumption goods			
Unprocessed	26	27	31
Processed	43	50	65
aterials for capital goods			
Unprocessed	23	28	32
Processed	38	40	55
oods			
Consumer durables	81	85	91
Machinery and equipment	14	17	22

Sources: 1959/60 and 1960/61 from Radhu [20, p. 551].
1964/65 unpublished supplementary table in Radhu [21].

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he development of increasingly liberal policy is traced out by Naqvi [7] and, with esti- the quantitative importance of specific measures, by Thomas [23].

r indirect support of this proposition, *see* the results of Pal's study [17].

A second theme implicit throughout the Panel report was *integration*—the hydrological problems of the Indus Plain can best be handled on a unitary or "systems" basis. Three kinds of integration are involved.

1) The Plain as a whole and its water supply must be considered as a unit. What is done to irrigate farm fields in former Punjab and Bahawalpur profoundly affects former Khairpur and Sind. The total water *requirement* for given cropping patterns and intensities in areas of given size throughout the Plain depends primarily on the potential evapotranspiration in these areas. It must be entered in any budget of irrigation water. But more important, because water in the Indus Plain is scarcer than arable land, is the total water *supply* from rivers and rain, and from surface and underground storage. We want to know the supplies (from both irrigation and effective rainfall), that can be made available during each month in each area at given levels of development of water structures. Comparisons need to be made of the social and economic costs and benefits of water developments in the Northern and Southern regions and their sub-regions. For each sub-region, with any given cropping pattern and intensity, the available water supplies will determine the size of the cropped area. The ultimate potential water supply for irrigation in the Plain as a whole is particularly significant, because it will fix the ultimate dimensions of the gross sown area, that is, the product of the cropping intensity times the net cultivated area. This must be the primary boundary condition in long range planning for agricultural development. The degree and speed of approach to this boundary condition are crucial for shorter range planning.

2) Irrigation water supplies from rivers and surface storage and from the underground reservoir should be managed as a single system. There is a marked seasonal variation in river flows, and a lack of concordance between these flows and the crop water requirements. At the same time, the unit costs of surface storage are high, and good reservoir sites are scarce. Consequently, the proportion of river waters effectively usable for irrigation can be raised near to its potential level only if sufficient underground water supplies are also available, at the right times. Conversely, the full potential of the underground reservoir can be realized, and a high percentage of recovery of the seepage from canals, water courses, and field percolation attained, only if river waters are available at the right times and places for mixing with relatively salty or sodium-rich underground waters.

3) Supply and drainage of irrigation water should be closely integrated. To maintain soil salinity and alkalinity control, a substantial fraction of the irrigation water applied to the fields must be drained off, either in conveyance channels or by percolation into the ground, and hence cannot be used consumptively in evapotranspiration by the crops. To minimize this fraction, to postpone investments for drainage, conveyance channels, and to reduce the ultimate costs of drainage structures, it is necessary to use the underground reservoir as an integral component of the drainage system. Any ultimate tubewell system should be designed to accommodate both irrigation supply and drainage.

THE BUDGET OF IRRIGATION WATER

In a steady state, rivers and rainfall are the only sources of supply for water in the Indus Plain. While there are significant fluctuations from year to year, the average annual volume of river flow is about 136 MAF (million acre feet), and the "effective" rainfall perhaps another 10 MAF. Of the total, say 145 MAF, only about a third was available in 1960 for beneficial use by crops. A large part of the remaining two-thirds flowed to the sea unused during the months of the summer monsoon; a smaller part was lost in non-beneficial evapotranspiration from rivers, canals, and water courses and their soggy banks, and from field ditches and edges. More than a third of the water diverted from the rivers into canals seeped into the ground, as did a small part of the river flows. A major fraction of the seepage was ultimately lost in non-beneficial evaporation from waterlogged and saline areas, where the watertable stood close to the surface.

A principal objective of water development in the Indus Plain is to contribute to increasing agricultural production by increasing the fraction of the total water supply that is beneficially used. Most of the beneficial use will be in evapotranspiration by crop plants, which from the standpoint of water transfer, behave much like little evaporating pans. But part of the beneficial use—ideally 10 to 15 per cent of the water applied to the fields—will be in achieving and maintaining a low salt content in the soil. This portion of the water will be used to wash away the salts already present or carried onto the fields with the irrigation water.

In the ultimate water development, the water running to the sea will consist very largely of these irrigation return flows. They will be needed to carry salt off the fields and out of the Plain. The principal device for increasing the usable supplies will be water storage during the monsoon months, either in surface reservoirs or underground, and the use of this stored water during the remainder of the year. As much as possible of the seepage water will be recovered, chiefly by pumping from wells. Part of the seepage enters the ground in areas of high groundwater salinity such as characterize the Southern Zone. It will not be recoverable for beneficial use, and will have to be wasted to the sea or to desert salt lagoons. Non-beneficial evapotranspiration losses will be minimized by careful water management, but these losses may actually be increased by surface storage.

Taking all factors into account, the Water and Power Development Authority of West Pakistan (WAPDA) has estimated that after construction of sufficient storage facilities, an average of some 114 MAF per year of river waters could ultimately be made available at the water courses leading to the farm fields[2]. The remaining 22 MAF would be lost, chiefly by non-beneficial evapotranspiration from reservoirs, link canals, rivers, irrigation canals, water courses, and from the border areas of all these various kinds of channels. WAPDA's estimate is based on an ultimate steady state in which only the average annual water supplies from rivers and rain can be considered. The approach to such a steady state will inevitably be slow and expensive, because it involves very extensive construction of dams, conveyance channels, and other surface water structures. In the meantime, there is an overwhelming need to increase agricultural production in West Pakistan as quickly and inexpensively as possible. Although chemical fertilizers, improved seeds, and other production factors can contribute to this end, water is the key. Here, during the transition period, we can utilize one of the great natural resources of the earth—the enormous pool of fresh groundwater that underlies the Northern Zone of the Indus Plain, and is equal in volume to ten times the annual flow of the rivers.

In making up irrigation water budgets for this transition period, we can base our calculations either on the water requirements for an assumed cropping pattern, cropping intensity, and net cultivated area, or on the estimated supplies that can be made available at a particular time with a given level of expenditures for water development. A budget based on assumed crop requirements has the advantage that the water needed during each month can be calculated. A budget based on the anticipated availability of supplies can give only seasonal totals until a cropping pattern is specified, but it has the great merit that comparisons of different cropping patterns can be made and the economic optimum chosen.

A Water Budget Based on an Assumed Cropping Pattern

Table 1 gives an irrigation water budget based on requirements for assumed cropping patterns and intensities on a net cultivated area of 19.4 million acres in the Northern Zone, and 7 million acres in the Southern Zone. The budget is computed from data given in a report by Harza Engineering Company International, made in 1963[3]. The total irrigation requirement at the water courses is 108 MAF and the beneficial use on the fields (evapotranspiration by crops *plus* leaching) is 83 MAF.

While the second design entailed a much smaller investment in wells and would require considerably smaller power costs than the first, it had the marked disadvantage of providing water sufficient for the intensive development of only 11.6 million acres of cultivated land. This area is a great deal less than that occupied at the present time. Farming could be maintained over the present area only at the cost of a relatively low intensity of cultivation.

The first scheme was shown to be economically more efficient than the second when the discount rate was taken as 4 per cent per year. At this discount rate, the present value of the time stream of benefits and costs of the mining scheme was 8 per cent larger than that in which recharge only was pumped. Moreover at *all* other discount rates from 0 to 10 per cent per year the first scheme outranks the second. The ranking is insensitive to the discount rate and the Panel Plan with 100-foot mining and large scale tubewell development affords a better investment than the second scheme.

The opinion has been expressed by some that the Panel Plan did not sufficiently take into account the difficulty that in mining over time the quality of groundwater will deteriorate due to the fact that salinity generally increases with depth. The Panel examined many hundreds of profiles of salinity and found that while this increase occurs in many places—indeed most places—the reverse is also true, and the *average* increase in salinity in 100 feet of depth was not large. Moreover, there are factors that operate to *improve* the quality of the groundwater over time. Several of the curves of salinity *vs.* time [1, Chapter 7] Figures 7.18 and 7.19 show a decrease in salinity after 30 years of operation. This decrease would have been even greater if the salt-flow model had been run under the plausible assumption that with a low watertable some of the salt leached below the root zone would be stored permanently in the soil pores above the watertable.

The Panel's principal argument for mining, however, did not rest upon the foregoing economic analysis. A more realistic but less quantifiable argument is that until a very large amount of surface storage is built, intensification of water use and cultivation can be accomplished in the Northern Zone only by mining or by greatly reducing the area of cultivated land. The latter would result in large social costs and perhaps monetary costs of resettlement and other adjustments.

Ghulam Mohammad's Budget for the Northern Zone[4]

A somewhat similar argument applies to the budget given by Ghulam Mohammad. Although he does not recommend a marked reduction in net cultivated area, his gross sown area in the Northern Zone would be much smaller than ours or Harza's and his cropping intensity lower. He assumes almost as much diversion of river waters at canal heads, but only 16 MAF of tubewell supplies, because he believes that about half the seepage water from canals and water courses, after mixing with the underground water, will be too salty or too sodium-rich to be usefully recovered by pumping. Although he does not mention the Southern Zone, by implicatin he allots it only a minor fraction of the canal diversions, since he states that his diversion scheme for the Northern Zone follows Harza's. He neglects non-beneficial evapotranspiration, but we have included this in recomputing his budget.

THE ROLE OF PUBLIC AND PRIVATE TUBEWELLS

At the time the Panel Report was written, the vigorous growth of privately installed and operated tubewells was not anticipated. About 30,000 such tubewells have now been installed, and they are making a significant contribution to the productivity of agriculture in West Pakistan. This contribution will grow as the private tubewells continue to be installed at a rate of several thousand units a year. The policy of the government in designing new SCARP and new public tubewell fields should, of course, take this development into account in order that the maximum benefit to the economy can be realized from the public and private tubewells together.

It must not be thought that this is simply a question of public versus private ownership. The public and the private tubewells differ from each other technologically and they will be operated in accordance with different principles and purposes. From the planner's point of view each is suitable for obtaining a somewhat different set of goals. The more appropriate mode for developing the underground water resources of any particular area will depend upon the conditions and problems prevalent in that area. The private tubewell owners have already recognized this. Although the private tubewells are quite widely dispersed throughout the irrigated region of the Plain they tend to be much more heavily concentrated in the upper regions of the *doabs* than elsewhere. We can make only a few tentative remarks on the four-way integration of public tubewells, private tubewells, canals, and drainage works, and feel that the situation must be watched closely and a sound policy developed in the light of experience. Our understanding of the operating characteristics of the private tubewells is especially deficient in spite of the excellent beginning that has been made by the two sample surveys of their operations, one conducted by Ghulam Mohammad [5] and the other by Harza Engineering Company International [6].

From a technical point of view the major differences between the two types of well are in capacity and depth. The public wells are designed for a capacity of from 3.5 to 4.5 cusecs (7 to 9 acre feet per day) and have a draft of from

250 feet to 350 feet. They are intended to provide water to an area of 600 acres or more each. The private wells are much smaller. Typically their flows are from 1 to 1.25 cusecs (2 to 2.5 acre feet per day) and their drafts are typically about 100 feet. The usual practice is for the private wells to serve an area of approximately 60 acres, or 1/10 that of the public wells.

From an economic point of view, it is pertinent that the public wells are built with imported components for the most part, while the private wells use equipment of domestic manufacture. The private wells, therefore, economize on the use of foreign exchange and also contribute to the accumulation of domestic manufacturing capacity and experience.

It is evident that the larger public wells are more efficient technically than the private ones. As will be discussed more fully in a later section the deeper draft of the large wells slows down the rate of salt build-up in the groundwater reservoir which is an inevitable result of the vertical drainage entailed by either system. The larger wells with their larger and more rugged pumps and motors, are also more efficient mechanically. It is very difficult to compare the costs of the two types of wells. Ghulam Mohammad has done so [7] and come to the conclusion that private wells can pump underground water more cheaply than government wells. This finding, however, should not be regarded as conclusive. The basic difficulty, aside from the fact that the government wells and the private ones are not in strictly comparable locations, is that different systems of accounts are used in computing the costs of the two systems of well. The cost accounts for government wells include charges for many items that the account for private wells omit, because the recorded cost for private wells incorporates only the out-of-pocket cost of the well owners. Costs of planning, supervision, and provision for contingencies, for example, are included in the government accounts but not in those for private wells, although the same economic functions must be performed in both instances. A good justification can be given for excluding the imputed costs of such functions from the estimate of the cost of private tubewells. These exclusions do, however, impair the comparability of those costs with the cost of government wells. The government accounts include costs for draining saline effluent and for power transmission; private accounts do not. And there are many other similar items.

With these reservations in mind, we have tried, in Table IV, to place the costs of water pumped by private and government wells on a comparable basis, relying largely on Ghulam Mohammad's data. Costs of drainage are omitted; they would be somewhat larger for the private wells than for the government ones because the quality of the effluent would deteriorate more rapidly from the shallower wells. All costs for the provision of power are included in the charge of Rs. 0.08 per kwh, used for both types of installation. In other respects too the two systems have been put on as comparable a basis as possible, as the source notes indicate in detail.

The computation shows that water pumped by private tubewells costs about 8 per cent more than water pumped by government wells. In view of the inherent lack of precision of such a calculation this difference should not be taken seriously; to all intents and purposes the calculation indicates that the costs of water from the two types of well are approximately the same. It should be noted, however, that in Table IV we have assumed the same load factor for both types of well, approximately 25 per cent. This load factor accords with the recorded experience with private wells but the public wells in the SCARP have been operated at a load factor of about 60 per cent. If the more intensive use of government as compared with private wells should persist, then the government wells will show an appreciable economy in comparison with the operating costs of the private wells.

At any rate, such cost comparisons cannot be decisive, because, as remarked above, the private and the public wells serve different purposes in the overall development of the Indus Plain. Private wells have been used only for very local supplementation of the supplies of canal water. Water provided by private tubewells is approximately four times as expensive as government canal water to the owner of the private well, and to a farmer who purchases from a private well owner, the discrepancy is even greater. Private wells will therefore be developed only in areas that have adequate supplies of high quality groundwater and they will be used mainly to fill in gaps in the supply of canal water. They have not been installed thus far in localities where the groundwater is too saline to be applied to the land without dilution with canal water. From the farmer's point of view the supply of government water from either wells or canals is less reliable than that of water provided by a locally owned tubewell and the government wells cannot be adapted as flexibily to day by day changes in the local requirements for irrigation water. On the other hand, the government wells can be used for the dilution of saline groundwater, for reclamation of deteriorated lands, and for closely integrated management of both ground and surface water supplies.

The advantage of closely coordinating canal diversions and groundwater withdrawals can be seen from a simple calculation based on the data in Table II. Suppose in the first instance that Mangla and Tarbela Dams are operating but that no tubewell water is available, and that the maximum amount of canal water available during any month in *kharif* is 12.4 MAF at the canal heads, or 8.7 MAF at the water courses, this being the maximum capacity of the canals.

This is only 65 per cent of the water requirement of 13.4 MAF in June, the critical month, so that under these conditions the entire program would aveh to be scaled down by 35 per cent. This scaled-down program would use only a total of 41 MAF of canal water at the water courses in *kharif* (59 MAF at the canal heads). On the other hand, if tubewells capable of providing 4.7 MAF per month (equivalent to a total well capacity of 80,000 cusecs) are available and suitably distributed over the cultivated area, then the required 13.4 MAF can be delivered to the water courses in June. The total delivery capacity of the canals can be utilised for irrigation from May through September, and 49 MAF of canal water can be delivered usefully to the water courses, corresponding to a diversion of 70 MAF at the canal heads. The tubewells not only supply 14 million acre feet in *kharif* but they make it possible to use 11 MAF of river water that would be wasted without them.

Similar calculations can be made for other assumed canal capacities, and they show in each case that the volume of beneficially usable river water during *kharif* can be increased by supplementing canal flows with sufficient pumping at the proper times. The same utilization of surface water could be attained by enlarging the canals. But by coordinating canal and tubewell operations, investments for enlarging and modifying the canal system can be minimized. Even more important, difficulties of silting and erosion, and of inadequate check structures on distributaries and water courses can be at least partly avoided. With the "regime" canals of the Indus Plain, these difficulties arise from large differences in canal flows during different months.

This calculation, naturally, somewhat overstates the case. An accurate computation would have to take account of the differing canal capacities and patterns of monthly irrigation requirements in the different canal systems, of the need for surface water to dilute saline groundwater, and of other complications. And, of course, perfect coordination cannot be attained. But the moral is clear that a closely integrated operation of tubewells and canals greatly increases the efficiency with which surface supplies can be used. This close integration can be more easily attained where government wells are installed than where private ones are. But it may be possible to integrate private wells with the canal operations through wide dissemination of information about planned canal operations and economic pricing policies for both canal and tubewell water. Even before adequate well capacity is installed throughout the Northern Zone, sufficient capacity may be developed in certain canal commands to test the scheme outlined in Table II, particularly the effectiveness of the incentives for the private operators.

One reason for the superior integration of government tubewells with canal operations is that this integration will require some changes from the historical patterns of canal diversions. It may be necessary or desirable to transfer surface supplies from one region to another, and to make good the transfers by additional pumping in areas underlain by high quality groundwater. These transfers will be more acceptable if reductions in surface water supplies are replaced by government-provided groundwater, but not if the deficit has to be made good by privately pumped groundwater, which, we have seen, is several times more expensive than canal water (*see*, for example [1, p. 280]).

Among the major benefits of the use of tubewells are the control of the level of the ground watertable and the reclamation of waterlogged and saline land. For these purposes government tubewells are much better adapted than private ones. The experience in SCARP I makes it clear that controlling the watertable requires coordinated operation of many tubewells covering a large area. Reclamation operations even when economically justifiable are not commercially attractive to private tubewell owners.

Private tubewell operations are also poorly adapted to exploiting the groundwater in regions where pools of poor quality water are interspersed among the good. If the level of the watertable is drawn down in regions underlain by high quality water to depths much below the average level, the neighbouring saline water is likely to infiltrate and to contaminate the remaining reservoir of sweet water. The long lives of some of the private tubewells indicate that this danger is not always present but it is clearly real in some places. Until accurate and detailed maps of groundwater quality can be made we must proceed with caution to avoid spoiling the underground water supplies.

Excessive lateral migration and mixing of saline with sweet groundwater can be prevented by operating all wells in a region as components of an integrated irrigation and drainage system, which is difficult when the wells are privately owned. On the other hand when problems of salinity control are likely to occur these problems may be intensified if the wells are operated by single farmer or small groups of farmers each pumping as much good quality water as he needs for his immediate use. Experience has been unsatisfactory in other countries when large numbers of privately owned and individually operated wells have been installed in regions where there are marked variations in the areal and vertical distribution of groundwater salinity.

The social effects of the private and public tubewells are also somewhat different. Water pumped by the government wells is available on the same terms to all farmers, while only the larger farmers, those operating farms of 25 acres or more, are likely to find it economical to install private tubewells. Small farmers can and do purchase tubewell water from the larger farmers, but the surveys available indicate that the prices are so high that the cost of installing a private tubewell is amortized in a period of 2 or 3 years. Therefore, in regions developed by private tubewell owners the underground water supplies will benefit primarily the larger farmers. Ordinary market forces cannot be expected to moderate the price of private tubewell water to small farmers because each small farmer will be located in a position that can be served by at most one or two large tubewells. In this circumstance, it may be adviseable to regulate the price of private tubewell water just as the terms for farm tenancy are now regulated. This regulation should not be so stringent that it erodes substantially the incentive for the installation of private tubewells where they are appropriate.

This all adds up to a complicated mesh of considerations that cannot be resolved finally until we have more experience with the operation of the private wells. Tentatively it appears that the private wells, being more responsive to local day-by-day requirements, are preferable in areas where they can be installed and operated profitably, and where considerations of control of groundwater quality are not overriding. They are managerially simpler to operate and they mobilize resources of private management and capital the government cannot tap. But where land reclamation or groundwater quality control are commanding considerations, and in areas from which surface water supplies should be diverted in the interests of overall economy, then the government tubewell developments are the method of choice. In the long run, there is also the question of coordinated operation of the canals and the tubewells in order to maximize the benefit from the high river flows of summer. We have suggested that it may be possible to do this with either private or public wells, but this should be tested. In any case, both sorts of wells have useful roles to play in the overall development of the Indus Plain.

QUALITY OF THE GROUNDWATER

Serious questions have been raised, most forcibly by Ghulam Mohammad [4], about the quality of the underground water in the former Punjab and Bahawalpur. These concern the salinity, or total salt concentration, of the water and the possibility of soil damage from an excessive sodium content in the presence of relatively high concentrations of carbonate and bicarbonate ions. Insufficient information exists to discuss such other problems as the potential hazards from boron, but we believe these are small.

Salinity

The Ground Water Development Organization of the Irrigation Department, and later the Water and Soil Investigation Division of the West Pakistan Water and Power Development Authority, made several thousand chemical analyses of water samples from nearly a thousand test holes, throughout 34 million acres of the Northern Zone. The total salt contents are summarized in Table V. We see that 16.3 million acres in the canal-irrigated regions of the former Punjab, and 2.0 million acres in canal regions of former Bahawalpur, overlie groundwaters with a salt content of less than 1000 ppm. These sweet water zones make up 70 per cent and 39 per cent, respectively, of the gross area in the canal-irrigated regions. Out of the entire 34 million acres, 21.2 million acres, over 62 per cent, have a salinity of less than 1000 ppm. There is no question that water in this salinity range can be used for irrigation, either directly or when suitably mixed with canal water. The area in the canal-irrigated regions underlain by this relatively high-quality water is close to the maximum net cultivated area, contemplated in Tables I and III for intensive cultivation.

To achieve the potentialities of the Indus Plain, it will be necessary to recapture as much seepage as possible from water courses, canals, and fields. Part of this seepage occurs in areas of salty groundwater. In the Panel Report, we assumed that groundwater with a salt content up to several thousand ppm could be used for irrigation if it is mixed with the river waters, which have a salinity of about 250 ppm. It is encouraging to note from Table V that less than 13 per cent of the entire Northern Zone is underlain by water with a salinity of more than 5000 ppm. In the canal irrigated regions, only 11 per cent of the gross area has a salinity in excess of 5000 ppm; 77 per cent has a salinity less than 2000 ppm.

In the Panel Report, we defined non-saline and saline areas as those underlain respectively by groundwater with a salinity less or more than 2000 ppm. The average salinity of water samples from the non-saline area (constituting 77 per cent of the canal region) is 750 ppm; the average for the saline area (constituting 23 per cent of the canal region) is 6000 ppm. The latter value is high because of the very high salinity of a few of the samples. If we consider instead the sizes of the areas overlying waters of different salinity, we can estimate, from Table V, that in half the saline area the groundwater has less than 5000 ppm, averaging 3350 ppm. A good deal of this water in the "favorable" half of the saline area can be used for irrigation, if it is sufficiently diluted with canal water.

We conclude that over the Northern Zone the distribution of groundwater salinity is so favorable that extensive exploitation of nearly all the area of the underground aquifer is warranted. In order to do this safely, however, highly saline waters must be pumped from underground and carried out of the region, perhaps to desert salt lagoons.

Extent of Sodium Hazard in Mixtures of Tubewell and Canal Waters

The Panel became aware during its first visit to Pakistan of the sodium hazard associated with use of groundwater in some areas. In evaluating the suitability of water for irrigation, an important parameter is the potential extent of exchange of sodium ions between the water and the dispersed phase of the soils. Absorption of too many sodium ions by certain soil clay minerals can cause excessive swelling of the dispersed phase. This may drastically reduce the permeability and porosity of the soil and decrease or destroy its agricultural value. The amount of sodium absorption depends on two factors: *i*) the ratio of sodium ions to the square-root of one-half the sum of calcium and magnesium ions in the soil water—this is called the "Sodium Absorption Ratio" (SAR); *ii*) the chemical and mineralogical nature of the clay fraction of the soils.

The SAR of the soil water depends on the SAR of the applied irrigation water and on its content of bicarbonate and carbonate ions. The latter tend to precipitate calcium in the soil as $CaCO_3$, and thereby to raise the SAR. In assessing the effect of bicarbonate and carbonate, the Panel used both the "residual" sodium carbonate (excess of carbonate and bicarbonate over calcium and magnesium in the applied water) and a new criterion developed by Dr. C. A. Bower, Director of the United States Salinity Laboratory at Riverside, California, and a member of the Panel. This criterion combines a modified Langlier index with the Sodium Absorption Ratio [8] to give a calculated "Exchangeable Sodium Percentage" (ESP).

Clays may be divided into three groups that have markedly different tendencies to swell with absorption of sodium ions: *i*) the kaolin group with a 1:1 lattice type; *ii*) the hydrated mica group with a 2:1 lattice type; and *iii*) the montmorillonite or expanding lattice group with a 2:1 lattice type. Soils containing clays of the montmorillonite group (beidellite, saponite, *etc.*) have a large intramicellular surface and a strong tendency to expand when the soil water has a relatively high ESP. The kaolin minerals (kaolinite, nacrite, metahalloysite, *etc.*) and hydrated mica minerals (illite, chlorite, *etc.*) have fixed lattices and exhibit much smaller hydration and absorptive properties. Soil samples from the irrigated regions of West Pakistan that were examined by the Panel contain clays predominantly of the non-expanding type such as illite and chlorite. These soils tolerate larger concentrations of exchangeable sodium in irrigation water than soils containing montmorillonitic clays.

After collecting and examining field data available in 1961 relating to the chemical composition of soil and water, the Panel decided that we had insufficient information to establish the magnitude of the sodium hazard. Accordingly, we arranged to carry out an investigation under Dr. Bower's guidance. During 1962 and 1963, chemical data from West Pakistan were sent to Riverside, and also to Cambridge, Massachusetts, for statistical analysis and evaluation. Dr. Bower carried forward a theoretical analysis of the various chemical processes at the soil-water interface that govern the uptake of sodium ions upon the clay lattice. This analysis was published by Bower and Maasland [8]. Maasland, Priest, and Malik [9] have summarized the results of the field and laboratory tests as well as the analytical studies.

In the water budget presented in Chapter 7 of the Panel Report, the predicated constraints pertaining to limiting mixing ratios of groundwater to surface water in the saline and non-saline areas were based on analyses of water from tubewells in the SCARP I project area and of water samples from elsewhere in the Northern Zone, made by the Water and Soils Investigation Division of WAPDA. The results are contained in items I C 7(a) and 7(c)(1)(2)(3) and (6) of the water budget. We estimated that in the non-saline areas of the former Punjab and former Bahawalpur the dilution ratio for one-third of the wells must be at least 1:1, while in the saline areas one-half the wells must have a dilution ratio of 2:1. These degrees of dilution were adequate to reduce the ESP to the range of 15 to 20 which we considered as generally safe for the soil types of the Northern Zone. As Maasland, Priest, and Malik show, reduction of the ESP to the commonly accepted "safe" range of 10-15 would require much higher dilution ratios. For example, in 40 per cent of the wells in the non-saline area, 2.5 parts of canal water would be needed for 1 part of tubewell water. However, a reduction to this extent is probably not necessary with the mica-type clays of former Punjab and Bahawalpur.

The Panel Report states the mixing ratios of canal to tubewell waters, as well as other design constraints based on groundwater salinity, in the form of inequalities, rather than equalities. In the final solution (IC 7(e)) for the water budget, several of these constraints were not binding. For example, if 77 per cent of the canal water is used in the non-saline area (*see*, Table III), the ratio of canal water to tubewell water at the water courses in the non-saline area is 70 per cent greater than that specified in the Report as a lower limit. In the saline area, if "skimming" wells can be used to recover canal seepage before it has become mixed with the salty underlying groundwaters, the salinities of the tubewell water may be lower than the calculated values.

The Panel Report contemplated that only 75 per cent of the area in the non-saline zone and 50 per cent of the area in the saline zone were to be cultivated. It should be possible to "pick and choose" favorable locations. In the non-saline zone, the groundwater over the best 75 per cent of the area may be expected to have a lower salinity and ESP than that predicated in the constraints of the water budget. As we showed above in discussing the distribution of salinity in the saline zone, the best half of this zone should overlie water with an average concentration of 3350 milligrams per litre.

On the basis of presently available water quality data, it is not possible to specify mixing ratios and irrigation rates or times in the various project areas with any degree of certainty, and the Panel made no attempt to do this. Any practical irrigation scheme depends on several factors. A water supply of a given salinity and alkalinity suitable for one soil type may be unsuitable for another. A given irrigation time or leaching rate appropriate for one blend of surface and groundwater may be inappropriate for another. A program of water management for sugarcane may be unsatisfactory for pulses. It may be expected that practices will vary over a wide spectrum in the various canal commands and project areas of the Plain, depending upon local conditions. In the Northernmost Zone, for example, the diluting effect of rainfall should be taken into consideration.

In spite of these uncertainties, the Panel Report did conclude, we believe reasonably, that integrated use of groundwater and canal water for irrigation can be safely undertaken throughout most of the cultivated area in former Punjab and Bahawalpur. Consequently, major investments to construct many large, deep tubewells are justified. In the following sections, further justifications for this conclusion are derived.

Salinity Control with Mixtures of Groundwater and Surface Water

The amount of irrigation water required to maximize crop production and control salination depends not only upon the consumptive use by crops but also upon the chemical quality of the water. The higher the salinity and/or the ratio of sodium ions to calcium and magnesium ions, the more water is needed. An extra amount, over and above the consumptive demands of the plants, must be allowed to percolate through the root zone. This will make it possible to maintain the concentration of salts in the soil water at a level such that growth will be sustained and excessive sodium absorption on the clay lattices will not occur. The critical period occurs at the end of the irrigation cycle just before watering, when the soil moisture is low and its salt concentration is high. The concentration at this time should be maintained at or below the tolerance level, which depends upon the particular crop and upon the type of soil. Two parameters are important in achieving salinity control: *i)* the total depth of water applied per crop or per year; and *ii)* the irrigation time, that is, the period between waterings.

Using Equation (2) and solving for C_a,

$$C_a = \frac{(W_a - ET)}{W_a} \cdot \frac{(W_f - ET)}{W_f} \cdot C_T \quad \text{......(3)}$$

The maximum permissible salinity of the applied water may be formulated as

$$C_a = R(I - P)\, C_T \quad \text{......(4)}$$

where P = the proportion of available water used during each watering period. Equation (3) may also be written in the form

$$C_a = \frac{D_a - ET/62.4}{D_a} \cdot \frac{D_f - ET/62.4}{D_f} \quad \text{......(5)}$$

where $D_a = W_a/62.4$ feet, and $D_f = W_f/62.4$ feet, represent respectively the depth of applied water and equivalent depth of water at field capacity.

To illustrate the use of the formulation, the following example is presented:

(1) A surface water of good quality has been used successfully to irrigate land in accordance with a management scheme in which a depth of water of 0.65 feet is applied every four weeks to a soil in which the field capacity is 0.80 cubic feet per square foot (50 pounds per square foot). The evapotranspiration rate is 0.15 feet per week and the maximum permissible concentration of salt in the pore water is C_T.

From Equation (5)

$$C_a = \frac{0.65 - 0.15\,(4)}{0.65} \cdot \frac{0.80 - 0.15\,(4)}{0.80}\; C_T \quad \text{......(6)}$$

$$C_a = 0.0192\; C_T$$

(2) A tubewell field is constructed to supply additional water to increase the acreage under cultivation. The tubewells not only increase the total water supply, but they make possible greater flexibility in the timing of water applications. However, because of the concentration of salt and exchangeable sodium in the groundwater, it must be mixed with surface water to protect the soil and assure agricultural productivity equivalent to that obtained where surface water alone is used. What will be the maximum permissible concentration in the blended water supply in a management scheme in which the irrigation rate per season (or per year) is increased 25 per cent and the watering period reduced to 1.5 weeks? The value of D_a will be (1.5/4) (0.65) (1.25) = 0.305 feet. Therefore from Equation (5),

$$C_a = \frac{0.305 = 0.15(1.5)}{0.305} \cdot \frac{0.80 - 0.15(1.5)\; C_T}{0.80} = 0.188\; C_T \quad \text{......(7)}$$

Since the value of C_T is the same in both schemes, it follows that salinity concentration in the mixture of surface and groundwater of the second scheme can be 0.188/0.0192 = 9.8 times larger than that of the first scheme. If the surface water has a concentration of 200 milligrams per litre, then the concentration of the mixed waters can be 2000 milligrams per litre, corresponding to groundwater with a salinity of 3800 milligrams per litre mixed (or alternated with) an equal volume of surface water. Moreover, if the relative concentrations of sodium, calcium, magnesium, bicarbonate and carbonate are the same in the irrigation water used in both schemes, there will be no deterioration of the soil in the latter scheme.

In a subsequent section of this paper (*see*, Equation (11)) we show that the leaching ratio and hence the value of C_a/C_T may be increased by increasing the pumping rate without affecting the other variables. It is evident from the foregoing analysis that integration of canal and tubewell irrigation water supplies can incorporate a large element of flexibility in salinity and alkalinity control.

Effects of Government and Private Tubewells on Salt Build-up and Drainage

The concept of a simple salt balance in a river basin was introduced a generation ago as a didactic device to illustrate underlying principles. Some elementary treatises on hydrology state that as an ideal a "favorable" balance should be maintained in which the efflux of salt from a region is not less than the influx. While this is patently desirable over a long span of time, it is far from being a valid design criterion that should be observed at all times, particularly in the first stages of a new era of investment in water resources. In our case a more rational criterion is to treat the vast aquifer of the northern plain as a primary resource to speed and sustain the economic development of West Pakistan. Hydraulic works for control of water and water quality should be installed in a carefully programmed sequence over a period of years. The optimal sequence may at different times entail a "favorable" salt balance in some regions, and an "unfavorable" balance in others. Decisions of this type can best be made using computer models for detailed simulation of project areas.

To maintain a salt balance, part of the irrigation water must be drained away from the region, and drainage channels must be constructed for this purpose. Drainage structures are expensive, and it will often be economically beneficial to postpone their construction for as long as possible. This can be accomplished in areas where both tubewell and canal waters are used for irrigation, if the salt is flushed out of the root zone and washed downward with recycled pumped water, to be stored underground. With typical private tubewells, which are usually only about 100 feet deep, the time interval before the underground water becomes so salty that drainage channels must be constructed will be relatively short, compared to the time available with typical "government" wells, which are usually about 250 feet deep.

Under some circumstances, early construction of drainage channels will be desirable, and in this case, when part of the irrigation water is drained off even in the early stages of development, the rate of increase of salt content in the underground water will be much slower than in the absence of drainage. Here also, the rate of build-up of groundwater salinity will be much less with deep "government" wells than with shallow private tubewells.

The following analysis, while not as versatile as the "salt-flow-model", presented in the Panel Report, shows the relationships involved. The system is assumed to be in a hydraulically steady state—the elevation of the watertable remains constant and inflows and outflows are balanced (*see* Figure 1)—but in an unsteady state as regards the salt content. This quantity initially may be larger or smaller than that in a steady state. The formulation shows the final concentration in the aquifer, the rate at which the system approaches salt equilibrium, and the significant design parameters.

Let

Q_c = inflow to irrigated area from canal system, acre feet per unit time;

Q_r = recharge from canal leakage and other sources, acre feet per unit time;

Q_e = evapotranspiration rate, acre feet per unit time;

Q_d = drainage flow, acre feet per unit time;

Q_w = flow through tubewells, acre feet per unit time;

$A = n\pi r_o^2$ = total area of well influence, acres or square feet; n is the number of wells; r_o is the radius of influence of a single well; and $2r_o$ is the (approximate) well spacing, feet.

γ = the proportion of total area cropped ;

γA = is the area under cultivation;

E = evapotranspiration rate, feet per unit time.

It is assumed that recharge and throughput are uniformly distributed over the aquifer. For a hydraulic balance over the entire system

$$Q_c + Q_r = Q_e + Q_d \qquad \text{(8)}$$

where

$$Q_e = E\gamma A = En\gamma r_o^2\pi \qquad \text{(9)}$$

The irrigation supply derives from the canal system and the tubewells.
The irrigation rate will be

$$\Delta = \frac{Q_c + Q_w - Q_d}{n\gamma r_o^2\pi} \qquad \text{(10)}$$

The throughput including flow recycled from watercourse seepage will be

$$Q_c + Q_w - Q_d - En\gamma r_o^2 \pi \geqslant 0$$

and the leaching ratio (*see,* Equation (1)) will be

$$R = \frac{Q_c + Q_w - Q_d - En\gamma r_o^2 \pi}{Q_c + Q_w - Q_d} \geqslant 0 \quad \text{...(11)}$$

Equation (11) shows that the leaching ratio may be increased by increasing Q_w without changing any of the other variables. Accordingly, in Equation (4) an increase in Q_w will increase the maximum value of the salt concentration of the mixed irrigation water supply. The flow in the well will include both the throughput and recharge. The salt carried into the groundwater in the throughput of the irrigation water and in seepage from the distribution system is assumed to be uniformly distributed over the area. The salt initially in the aquifer is assumed to be distributed uniformly throughout the groundwater. Under these assumptions and the further assumption that complete vertical mixing of the salt occurs during the travel to the well, the salt concentration will be the same in all parts of the groundwater and will increase everywhere at the same rate.

If the salt concentrations in the groundwater and in the canal water are denoted by C and C_c respectively, then the weight of salt entering the groundwater during unit time will be

$$C_c (Q_c + Q_r) + C (Q_w - Q_d)$$

and the amount leaving will be CQ_w. Therefore, the rate of increase of salt in the aquifer will be

$$nS\pi r_o^2 h \frac{dC}{dt} = C_c (Q_c + Q_r) + C (Q_w - Q_d) - CQ_w$$

$$\frac{dC}{dt} = \frac{C_c (Q_c + Q_r) - C\, Q_d}{nS\pi r_o^2 h} \quad \text{....................................(12)}$$

where S = the storage coefficient of the soil and h = effective depth of the well. Equation (12) may be integrated to give the following time-path for the salinity concentration in the groundwater:

$$C = [C_c (Q_c + Q_r)/Q_d]\,[1 - \exp(-Q_d t/nS\pi r_o^2 h)] + C_g \exp(-Q_d t/nS\pi r_o^2 h) \quad \text{.....................................(13)}$$

where C_g is the initial salt concentration of the groundwater.

If the rate of drainage is very small or zero, Equation (13) may be written in the form of a linear equation in which the time rate of increase of the groundwater salinity is constant. The time required for the concentration to reach a specified maximum value C_m may be computed from the following equation.

$$t = \frac{SAh}{C_c(Q_c + Q_r)}(C_m - C_g) \quad \text{.......................................} (14)$$

Values of t for a range of soil salt contents from 0 to 50 tons/acre and for well depths of 50 to 250 feet are given in Table VI. In part I of this table, the initial salt concentration in the groundwater is taken as 500 mg/1; in part II, it is 750 mg/1. These values were chosen in order to keep well within the range of conditions where there is general agreement that tubewells can be used [4]. For privately operated tubewells, it will be difficult to attain an "optimum" mixing ratio of tubewell and canal waters. Hence C_m is taken as 1500 ppm. We have assumed that the volume of canal water plus river recharge is 3.3 acre feet/acre/year, C_c is 250 ppm, and S is 0.25.

The times given above are those required for the *average* salinity in the groundwater layer which is supplying the well to reach 1500 ppm. As shown in the Panel Report, the time required for the well water to reach this salinity (after a brief initial period) will be somewhat longer than the above values, because thorough mixing does not occur in the aquifer. *But the delay due to imperfect mixing will be short for shallow wells, and long for deep wells.*

It is clear that relatively shallow tubewells without drainage channels to maintain a salt balance will become excessively salty in a few years, if they are used in areas where there is a significant initial salt accumulation in the soil. Within a few years after the tubewells are installed, channels will have to be constructed to carry away salty groundwater. If the salty water has a salinity of 1500 mg/1, the minimum amount of water that will need to be carried away will be 1/6th of the total canal supply, including that which enters the ground as recharge. Unless the conveyance channels are lined, about 25 per cent of the total water supply will have to be run into them, to make up for leakage. But part of this will, of course, be recovered by the wells. However, the 1/6th of the total supply that cannot be used will reduce the gross sown acreage.

Equation (14) and Table V give the time for salt build-up before surface drainage is installed. If soil drainage exists from the beginning, Equation (13) applies. The ultimate concentration in the groundwater, will then be $C_c(Q_c + Q_r)/Q_d$. However, the time elapsed before a salt balance is attained may be very long. For example, if $C_c = 250$ milligrams per liter and $(Q_c + Q_r)/Q_d = 8$, then the ultimate concentration will be 2000 milligrams per litre. If $Q_d/n \pi r_0^2 = 0.25$, $S = 0.25$ and $C_g = 750$ mg/l the salinity of the groundwater and the tubewell water at various times is given in Table VII for tubewell depths of 100 and 250 feet.

"Horizontal" versus "Vertical" Drainage

Any drainage system in an irrigated area must serve two purposes: *i*) removal of excess water and control of the elevation of the watertable; *ii*) removal of saline water to prevent accumulation of salt in the soil. These objectives can be accomplished in one of two ways: *i*) by pumping water from underground and carrying part of the pumped water away from the region in conveyance channels; or, *ii*) by allowing part of the irrigation water to percolate into a series of small ditches or porous tile pipes, which lead into larger "collector" and "main" drains. Such a "horizontal" system can be used to remove saline waters only if the watertable is sufficiently close to the surface to prevent a major part of the irrigation return flows from seeping out of the drains. The system is not effective for salinity control in a region where both ground and surface waters are being used for irrigation and the watertable is pumped down significantly below the bottom level of the drainage channels during part of the time. Wherever large numbers of tubewells, either public or private, are employed to supply part of the irrigation water, it will often be undesirable to keep the watertable high. Horizontal drainage structures will then have a limited usefulness, primarily to carry off flood waters. In regions of highly saline underground water, tubewells will not be employed to provide irrigation supplies, and either a horizontal system or a system of tubewells plus conveyance channels can be employed for drainage. Several factors should enter into the choice between these alternatives.

Horizontal drainage may be economical in certain regions of West Pakistan, particularly in parts of the Southern Zone, where conditions for vertical drainage are not satisfactory. In the Panel Report, however, we concluded that vertical drainage would be desirable in most areas of the Indus Plain.

The principal disadvantage of horizontal drainage is that it must operate with a relatively high watertable, and hence is incompatible with the use of tubewells to increase and stabilize the irrigation water supply. But other disadvantages must also be kept in mind.

1) A system of main drains and tile or open field drains is essentially a passive system. It is dependent upon gravity flow and once it is constructed it cannot easily be modified or revamped. The amount of water discharged through such a system depends upon the amount of water applied to the land it subtends, and the salt removed in drainage depends largely upon the salinity of the upper

layers of the groundwater. The flow in the main drains and laterals depends on seepage rates and these in turn depend upon the gradient of the watertable. A vertical drainage system, on the other hand, is more flexible. The flow and salinity of the mixed effluent of a set of tubewells can be controlled, and consequently, drainage can be carried out at any desired rate. This results both in a smaller investment in conveyance channels and in better salinity control, because salt can be returned to the rivers during periods of high runoff, or routed to salt lagoons at times when the irrigation requirement is small.

Compared with vertical drainage, horizontal drainage systems are wasteful of water. The salinity concentration of the drained water is likely to be smaller than with tubewell drainage and hence larger amounts of water must be carried away in the drains.

2) In flat topography it is difficult to fit together efficiently a horizontal drainage system with an intensive irrigation system. Crossings of conveyance lines of the two systems are unavoidable and are expensive. If the drainage is to be returned to the canals, pumps are required. The principal costs of horizontal drainage in the Indus Plain would be associated with pumps and with concrete control and access structures including weirs, gates, check stops, bridges and pump sumps that cannot be built with unskilled labor.

3) Irrigated agriculture is most successful when it is most intensive, that is when it is concentrated on a minimum land area. Open drain systems occupy a significant portion of the land area in and between the cultivated fields and hence cause the farming operations to be spread out on more land. While it is true that the supply of good land is greater than the supply of water throughout most of the Indus Plain, the layout of an extensive horizontal drainage system, which must conform to the topography and have a minimum number of inter sections with the distribution system, will extend and complicate the access routes to the fields. Farming operations are impeded when bridges must be crossed.

4) Deep main drains and open field drains are difficult to maintain. Drainage works are sporadically impaired by flood damage and their efficiency is regularly reduced by growth of weeds. Flood damage to drains is inherently more serious than the damage to water distribution channels because of topography. Unless pumps are used, artificial drainage must conform with natural drainage. Consequently the drains must be adequate to handle storm runoff and must be repaired after the floods recede. Weed growth in drainage ditches is more abundant than in distribution channels because of lower flow velocity and greater nutrient supply. Maintenance of drains—removal of weeds and debris, channel realignment and repair of side slopes—is difficult and unpleasant work. Even a cow does not like to descend into the weedy morass of a malfunctioning drain.

5) In semi-tropical climate the stagnant water and swampy reaches of open drains may constitute a public health hazard. The ditches afford a favorable environment for the growth of mosquitoes and snails. In other countries endemic and epidemic levels of morbidity from malaria and bilharziasis have been caused by horizontal drainage works that have not been properly maintained.

A Comment on Sub-irrigation

One of the arguments for a horizontal drainage system is that by keeping the watertable close to the surface a considerable fraction of the seepage from canals and water courses can be recovered by the crops through sub irrigation.

In the historical development of most irrigation projects it commonly happens that at one time or another enthusiasm is generated over the possibilities of sub-irrigation as a cheap method of water distribution. When such schemes are tried, however, they are usually found to have serious limitations. In some cases they have failed completely and caused serious land damage. In the United States, there have been two exceptions where sub-irrigation has proved to be more than a fad. One of these is in the San Luis Valley in Colorado, and the other in the Snake River Basin in Idaho. In both of these places the following favorable conditions obtain:

i) the slopes of the land and watertable are relatively steep so that stagnation does not occur; and

ii) the soil and subsoil are permeable (in the San Luis project the soil is almost a fine gravel, in Idaho the aquifer is a coarse-textured volcanic ash). Sub-irrigation at these sites has worked because it is possible to drain the soil thoroughly during the non-irrigation season. The soil is recharged in the spring; after the harvest the watertable is lowered and the salt carried away.

We conclude that sub-irrigation, as well as conventional horizontal drainage, might find limited application in certain localities of West Pakistan under special geological and hydrological conditions. Neither of these methods warrant much attention, however, in the primary scheme of water resource development in the Indus Plain.

CONCLUDING REMARKS

Agricultural production has shown heartening progress in the past two or three years, particularly in regions where traditional supplies of irrigation water have been enhanced either by government tubewells, as in SCARP I, or by private tubewells as in the upper part of Rechna Doab. Farmers have taken advantage of the improved water supplies with admirable alacrity. The trends in crop yields per acre and particularly in the intensity of cultivation both reflect this. There is every reason to expect that with the opening of new SCARPS and with the continued spread of private tubewells this progress will persist Nevertheless we must reiterate that insufficient water was not the only deficiency in the Indus Plain and the provision of more water is not the solution to the agricultural problem there. It is only the first step and, we hope, the catalyzing step in a movement toward thorough-going agricultural modernization. We do not have to spell out again the other measures that are urgently demanded; the report of the Commission on Food and Agriculture and our previous Report have covered these measures in ample detail. We need here only state our impression that insufficient attention is being given to the other needs of agriculture in West Pakistan. Unless these other needs are met the ultimate results of all this effort will be disappointing. Yields will remain below world-wide averages, the ravages of insect and rodent pests will continue, and agricultural incomes will not advance as they should and must. The progress in the fields of agricultural extension, agricultural credit, seedstock improvement, and other directions has not been comparable to the progress made in improvements in water supply and in the use of fertilizer. We should like to conclude our review with an earnest plea that vigorous attention to these problems, admittedly difficult, be given the highest priority.

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TABLE 1

HARZA "PROGRAMME" IRRIGATION WATER BUDGET
PART I: REQUIREMENTS

	Northern Zone	Southern Zone	Total, Indus Plain
A. Assumed cultivated area (*million acres*)			
1. Net cultivated area[1]	19.4	7.0	26.4
2. Gross sown area[2]			
a. *Rabi*	17.5	2.6	20.1
b. *Kharif*	11.6	4.9	16.5
c. Total	29.1	7.5	36.6
B. Irrigation water requirement (*million acre-feet*)			
1. At water courses[3]			
a. *Rabi*	36	9	45
b. *Kharif*	46	17	63
c. Annual	82	26	108
2. Beneficial use on fields (Evapotranspiration by crops *plus* leaching)[4]			
a. *Rabi*	28	7	35
b. *Kharif*	35	13	48
c. Annual	63	20	83
C. Depth of water used beneficially on fields (*feet*)			
a. *Rabis*	1.6	2.7	1.7
b. *Kharifs*[5]	3.0	2.7	2.9
c. Annual[6]	3.2	2.9	3.1

Source: Computed from data and assumptions in [3].

[1] From [3, Table II-7].
[2] Computed from cropping patterns in [3, Tables II-9 and II-10].
[3] Computed from [3, Tables II-11 and II-12].
[4] Values in B.1 multiplied by .765 (*see* text).
[5] Values in B.2.a and B.2.b divided by corresponding values in A.2.a and A.2.b.
[6] Values in B.2.c. divided by corresponding values in A.1.

TABLE I (*contd.*)

HARZA "PROGRAMME" IRRIGATION WATER BUDGET

PART II : SUPPLIES

	Northern Zone	Southern Zone	Total Indus Plain
A. From river diversions (*million acre-feet*)			
1. At canal heads[1]			
a. *Rabi*	20	13	33
b. *Kharif*	46	24	70
c. Annual	66	37	103
2. At water courses			
a. *Rabi*	14**	9†	23††
b. *Kharif*	32**	17†	49††
c. Annual	46**	26†	72*
B. From tubewells, at water courses (*million acre-feet*)[2]			
a. *Rabi*	22	—	22
b. *Kharif*	14	—	14
c. Annual	36*†	—	36*†
C. Total supplies at water courses (*million acre-feet*)†			
a. *Rabi*	36	9	45
b. *Kharif*	46	17	63
c. Annual	82	26	108*†

[1] Values at water courses (*see* A.2.), divided by 0.7.

[2] Values in A.2 subtracted from corresponding values in C.

* 64.3 MAF [2, p. 28] *plus* 8 MAF [2, p. 29].

† From Part I: Requirements, values in B.1.

†† From Table II.

** Total diversions for Indus Plain—diversions for Southern Zone.

*† [2, pp. 28-30]. 64.3 MAF average diversions at water courses with present canal system must be supplemented by 44 MAF to meet irrigation requirements. Of this amount, 8 MAF can be obtained by enlarging canals, the remainder can be provided by groundwater pumping and additional reservoirs.

TABLE II

POSSIBLE AVERAGE MONTHLY WATER BUDGET IN THE INDUS PLAIN BASED ON HARZA "PROGRAMME" WITH PRESENTLY DESIGNED SURFACE STORAGE AND ASSUMED TUBEWELL AND CANAL CAPACITIES*

Month	At water courses			At canal heads			River and reservoir losses	
	Irrigation requirements	Supplies from canals	Supplies from wells	Total diversions	River flows	Changes in surface storage	Seepage and evaporation	To sea
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
			(.............*million acre-feet***	.............)				
October	11.1	6.4	4.7	9.1	4.6	—4.6	0.1	0.0
November	7.0	3.0	4.0	4.3	3.1	—1.3	0.1	0.0
December	5.3	3.0	2.3	4.3	2.6	—1.8	0.1	0.0
January	7.0	3.0	4.0	4.3	2.7	—1.7	0.1	0.0
February	5.6	3.1	2.5	4.4	2.9	—1.6	0.1	0.0
March	8.8	4.1	4.7	5.8	5.0	—0.9	0.1	0.0
Rabi total	44.8	22.6	22.2	32.2	20.9	—11.9	0.6	—
April	7.4	5.7	1.7	8.1	8.2	0.0	0.1	0.0
May	12.9	8.7	4.2	12.4	14.2	0.0	0.2	1.6
June	13.4	8.7	4.7	12.4	22.4	0.0	3.0	7.4
July	10.7	8.7	2.0	12.4	30.7	+7.3	4.0	7.0
August	10.5	8.7	1.8	12.4	26.8	+4.7	4.0	5.7
September	8.7	8.7	0.0	12.4	12.4	—0.1	0.1	0.0
Kharif total	63.6	49.2	14.4	70.1	114.7	+11.9	11.4	21.7
Annual values	108.4	71.8	36.6	102.3	135.6	0.0	12.0	21.7

Assumptions: * Live storage back of Mangla and Tarbela Dams = 12.0 MAF
Canal capacity—12.4 MAF/month = 207,000 second feet
Tubewell capacity ≥ 4.7 MAF/month = 78,000 second feet.
Annual losses from seepage and evaporation in rivers and reservoirs = 12.0 MAF [Harza, p. 29] states that 12 MAF are lost in natural river channels between the rim stations and diversion points.

** Differences between corresponding values in Tables 1 and 2 are due to rounding.

Sources: Col. (2): Computed from [3, Tables II-11 and II-12], combined with acreages and intensities of cultivation given in [3, Tables II-7, II-8 and II-9]; *see also* our Table I.

(*sources continued on next page*)

Col. (3): Column (5) × 0.7.

Col. (4): Column (2) — Column (3).

Col. (5): *Maximum* monthly canal diversions *during kharif* are limited by the assumed canal capacity of 12.4 MAF/month. *Average* monthly diversions *during rabi* are limited by the volume of water available in river flows plus surface storage; as Column (5) shows, this average is 5.4 MAF/month. With this limitation, the *maximum* monthly diversion *during rabi* is determined by the maximum difference between tubewell capacity and the irrigation requirement in any month. To minimize investment costs we have assumed that tubewell capacity is set by the amount of pumping needed in June—the month of highest irrigation requirement. This results in computed diversions of 9.1 MAF in October and only 4.3 MAF/month during November through January. Unless some canals are effectively non-perennial, the ratio between maximum and minimum canal flows of 12.4 to 4.3 may be too high to avoid difficulties of silting and erosion, and of inadequate check structures for gravity flow to water courses. These difficulties may exist even with a *kharif-rabi* ratio of 12.4/5.4

Col. (6): From [1, Table 1.2 and Figure 7.1].

Col. (7): Column (6)—[Column (5) + Column (8) + Column (9)].

Col. (8): River and reservoir losses from September through May are assumed to be principally by evapotranspiration. During June through August, evapotranspiration is greatly increased because of the spreading of the rivers in flood; in addition, there are major seepage losses during these months.

Col. (9): It may be possible to capture part of the runoff shown in this column through recharge of groundwater in the Southern Zone, provided additional tubewells are installed to pump out the aquifer near the Indus banks during the months of low flow.

TABLE III

COMPARISON OF AVERAGE ANNUAL IRRIGATION BUDGETS

	Harza "Programme" (1)	Panel (2)	Ghulam Mohammed (3)
A. Cultivated area (*million acres*)			
1. Net cultivated area[4]			
a. Northern Zone	19.4	17.0[5]	15.8
b. Southern Zone	7.0	9.5[6]	*n.g.*[7]
c. Total, Indus Plain	26.4	26.5	*n.g.*
2. Gross sown area[8]			
a. Northern Zone	29.1	28.4	20.7
b. Southern Zone	7.5	12.8	*n.g.*
c. Total, Indus Plain	36.6	41.2	*n.g.*
B. Cropping intensities (*in per cent*)[9]			
a. Northern Zone	150[10]	167	131[11]
b. Southern Zone	107[12]	135[13]	*n.g.*
c. Indus Plain	139	159	*n.g.*
C. Irrigation water supplies (*million acre-feet*)			
1. Diversions at canal heads			
a. Northern Zone	66	48[14]	61
b. Southern Zone	37	44	*n.g.*
c. Total, Indus Plain	103	92	*n.g.*
2. Canal supplies at water courses			
a. Northern Zone	46	30[15]	43[16]
b. Southern Zone	26	38[17]	*n.g.*
c. Total, Indus Plain	72	68	*n.g.*
3. Tubewell supplies at water courses			
a. Northern Zone	36	47[18]	16[19]
b. Southern Zone	0	11[20]	*n.g.*
c. Total, Indus Plain	36	58	*n.g.*

(*continued*)—

TABLE III (*contd.*)

	Harza "Programme" (1)	Panel (2)	Ghulam Mohammed (3)
4. Total supplies at water courses			
a. Northern Zone	82	77	59
b. Southern Zone	26	49	*n.g.*
c. Total, Indus Plain	108	126	*n.g.*
5. Beneficial uses on fields: crop evapotranspiration *plus* leaching			
a. Northern Zone	63	61[22]	45[21]
b. Southern Zone	20	36[23]	*n.g.*
c. Total, Indus Plain	83	97	*n.g.*
D. Annual depth of water used beneficially (*feet*)[24]			
1. On net cultivated area			
a. Northern Zone	3.2	3.6	2.8
b. Southern Zone	2.9	3.7	*n.g.*
c. Indus Plain	3.1	3.7	*n.g.*
2. On gross sown area			
a. Northern Zone	2.2	2.2	2.2
b. Southern Zone	2.7	2.7	*n.g.*
c. Indus Plain	2.3	2.3	*n.g.*
E. Water losses from canals, water courses and fields (*million acre-feet*)			
1. Total seepage[25]			
a. Northern Zone	29	24[26]	24
b. Southern Zone	14	13[27]	*n.g*
c. Total, Indus Plain	43	37	*n.g.*
2. Non-beneficial evapotranspiration[28]			
a. Northern Zone	15	10[29]	12
b. Southern Zone	6	7[30]	*n.g.*
c. Total, Indus Plain	21	17	*n.g.*

(*continued*)

Sources: Col. (1) From Table I.

Col. (2) From data and computations in [1, Chapters 5 and 7, pp. 192-193 and 269-284].

Col. (3): From [4, pp. 381-383].

[4] Canal commanded area planted at least once during the year *plus* fallow.

[5] In the Panel Report, the net cultivated acreage for the former Punjab and Bahawalpur is given as 16.4 MA, corresponding to "firm" canal diversions (4 out of 5 years) of 45 MAF. For comparison with Harza and Ghulam Mohammad we have used the Panel's average diversion of 48 MAF, which gives an increase of 3 per cent in the volume of water for beneficial use on crops. The net cultivated acreage is increased accordingly.

[6] Mean of range of 8 to 11 MA.

[7] *n.g.* = not given.

[8] Gross sown area = Net cultivated area × per cent cropping intensity/100.

[9] In computing cropping intensity, Harza counts the acreage planted to sugarcane during both *kharif* and *rabi;* in the Panel Report, the sugar acreage is counted only once, in *kharif.* Here we have used the Harza procedure.

[10] 60 per cent in *kharif* and 90 per cent in *rabi.*

[11] Per cent cropping intensity chosen to give same depth of water for beneficial use on the gross sown area (2.2 ft.) as in Column (1).

[12] 80 per cent in non-perennial area and 135 per cent in perennial area.

[13] Per cent cropping intensity chosen to give same depth of water for beneficial use on gross sown area (2.7 feet) as in Column (1).

[14] Average canal diversions to former Punjab and Bahawalpur.

[15] Seepage and non-beneficial evapotranspiration in canals are assumed to be 26 per cent and 12 per cent of canal head diversions, respectively.

[16] Seepage and non-beneficial evapotranspiration in canals are assumed to be 24 per cent and 6 per cent of canal head diversions, respectively, following Harza.

[17] Combined seepage and non-beneficial evapotranspiration in canals is assumed to be 13 per cent of canal head diversions.

[18] 41 MAF in the Panel's "non saline" area *plus* 6 MAF in the "saline" area.

[19] 12 MAF from canals, water courses and field seepage in Ghulam Mohammad's "non-saline area" and 4 MAF from "recharge from rain and river".

[20] Total pumping at water courses required to provide 8 MAF of well water for beneficial use on farm fields (8/(1—.26) = 11 MAF).

[21] Supplies at water courses—10 per cent losses in water courses and 15 per cent non-beneficial seepage *plus* evapotranspiration of water applied to fields. (.765 × water course supplies).

[22] Supplies at water courses—20 per cent losses in water courses and farm fields.

[23] Supplies at water courses—26 per cent losses in water courses and farm fields.

[24] Beneficial use = evapotranspiration from crops or cultivated fields *plus* water required for leaching.

[25] Except for Column (3), total seepage is assumed to be 37 per cent of diversions at canal heads *plus* 14 per cent of water pumped from tubewells.

[26] 35 per cent of diversions at canal heads *plus* 15 per cent of water pumped from tubewells.

[27] 26 per cent of diversions at canal heads *plus* 17 per cent of water pumped from tubewells.

[28] Except for Column (3) non-beneficial evapotranspiration is assumed to be 16 per cent of diversions at canal heads *plus* 14 per cent of water pumped from tubewells.

[29] 15 per cent of diversions at canal heads *plus* 5 per cent of water pumped from tubewells.

[30] 13 per cent of canal head diversions *plus* 9 per cent of water pumped from tubewells.

TABLE IV

COSTS OF WATER USING GOVERNMENT AND PRIVATE TUBEWELLS

Item	(A) Government tubewells	(B) Private tubewells
1. Direct construction cost (*rupees*)	51900	7800
2. Water distribution system and land (*rupees*)	3140	—
3. Net construction cost	47760	7800
4. Annual amortization factor (*at 6 per cent*)	.0872	.1359
5. Annual charge (*rupees*)	4165	1060
6. Rate of flow (*cusec*)	3.9	1.25
7. Output per year. (2200 operating hours) (*acre feet*)	710	227
8. Capital charge per acre foot (*rupees*)	5.88	4.67
9. Operating cost per day (*rupees*)	—	11.06
10. Output per day, (*acre feet*)	—	0.826
11. Operating cost per acre foot (*rupees*)	10.80	13.38
12. Total cost per acre foot (*rupees*)	16.68	18.05

Sources: Rows 1, 2: [7, Table B-I].

Rows 3, 4, 5: Computed. 20-year economic life assumed for government tubewells, 10 years for private tubewells.

Row 6: [7, Table B-I].

Rows 7, 8: Computed.

Row 9: [7, Table B-II].

Row 10: Computed.

Row 11: (A) from [1, Table 7.4, adjusted to power cost of Rs. 0.08 per Kw.hr]. (B) Computed.

Row 12: Row 8 + Row 17.

TABLE V

SALINITY OF GROUNDWATER IN NORTHERN ZONE

Salinity	Area underlain by groundwater of indicated salinity[1]				Total		
	Former Punjab[2]		Former Bahawalpur[3]				
	Canal regions	Non-canal regions[4]	Canal regions[5]	Non-canal regions	Canal regions	Non-canal regions	Total
	(......million acres......)						
Less than 500 ppm	9.9	0.1	1.2	—	11.1	0.1	11.2
500—1000 ppm	6.4	2.8	0.8	—	7.2	2.8	10.0
1000—2000 ppm	3.4	0.7	1.1	0.4	7.0	1.5	8.5
2000—3000 ppm	1.2	0.3					
3000—4000 ppm	0.6	0.1					
4000—5000 ppm	0.7	—					
5000—10,000 ppm	1.0	—	1.3	0.7	2.3	0.7	3.0
10,000—20,000 ppm	0.2	—	0.6	0.4	0.8	0.4	1.2
More than 20,000 ppm	—	—	—	0.1	—	0.1	0.1
Total gross area	23.4	4.0	5.1	1.5	28.5	5.5	34.0
Culturable commanded area	15.2	—	3.5	—	18.7	—	18.7
	(......*Per cent of gross area*......)						
Less than 500 ppm	29.2	0.3	3.5	—	32.7	0.3	33.0
500—1000 ppm	18.8	8.2	2.4	—	21.2	8.2	29.4
1000—2000 ppm	10.0	2.1	3.2	1.2	20.6	4.5	25.1
2000—3000 ppm	3.5	0.9					
3000—4000 ppm	1.8	0.3					
4000—5000 ppm	2.1	—					
5000—10,000 ppm	2.9	—	3.8	2.0	6.7	2.0	8.7
10,000—20,000 ppm	0.6	—	1.8	1.2	2.4	1.2	3.6
More than 20,000 ppm	—	—	0.3	—	0.3	—	0.3
	68.9	11.8	15.0	4.4	83.9	16.2	100.1

Source: From [3, Table II-5, Chapter II. Irrigation Development in the Indus Plain].

[1] Salinity as parts per million of total dissolved solids in groundwater samples at a depth of more than 100 feet.

[2] Includes Thal, Chaj, Rechna and Bari Doabs, but not Indus Right Bank areas.

[3] Areas under command of Fordwah, Eastern Sadiquia, Quimpar, Bahaw canals, *Plus* 1.5 MA of "undeveloped" area

[4] Includes 1.7 million acres in Gujrat Plain and Sialkot, where well irrigation is used, and 2.4 million acres of undeveloped and desert area in Thal Doab.

[5] 2.0 million acres commanded by the Panjnad Canal has been incompletely surveyed. According to Harza, about 50 per cent of this area is believed underlain by water with less than 1000 ppm of salinity. Accordingly, we have distributed the Panjnad Canal area as follows : 0.5 million acres less than 500 ppm; 0.5 million acres, 500-1000 ppm; 0.3 million acres, 1000- 5000 ppm; 0.4 million acres, 5000-10000 ppm; 0.3 million acres; 10000-20000 ppm.

TABLE VI

TIME OF BUILD-UP OF SALINITY IN UNDERGROUND WATER FOR TUBEWELLS OF DIFFERENT DEPTH

I. INITIAL GROUNDWATER SALINITY = 500 PPM
FINAL GROUNDWATER SALINITY = 1500 PPM

Well depth Feet	Soil salt, tons/acre	0	10	20	30	40	50
		Time in years to reach 1500 ppm in groundwater					
50		15.1	6.3	0	0	0	0
100		30.2	21.4	12.5	3.7	0	0
150		45.5	36.7	27.8	18.9	10.0	1.1
200		60.5	51.6	42.7	33.8	25.1	16.0
250		75.6	66.9	57.9	48.4	40.6	48.4

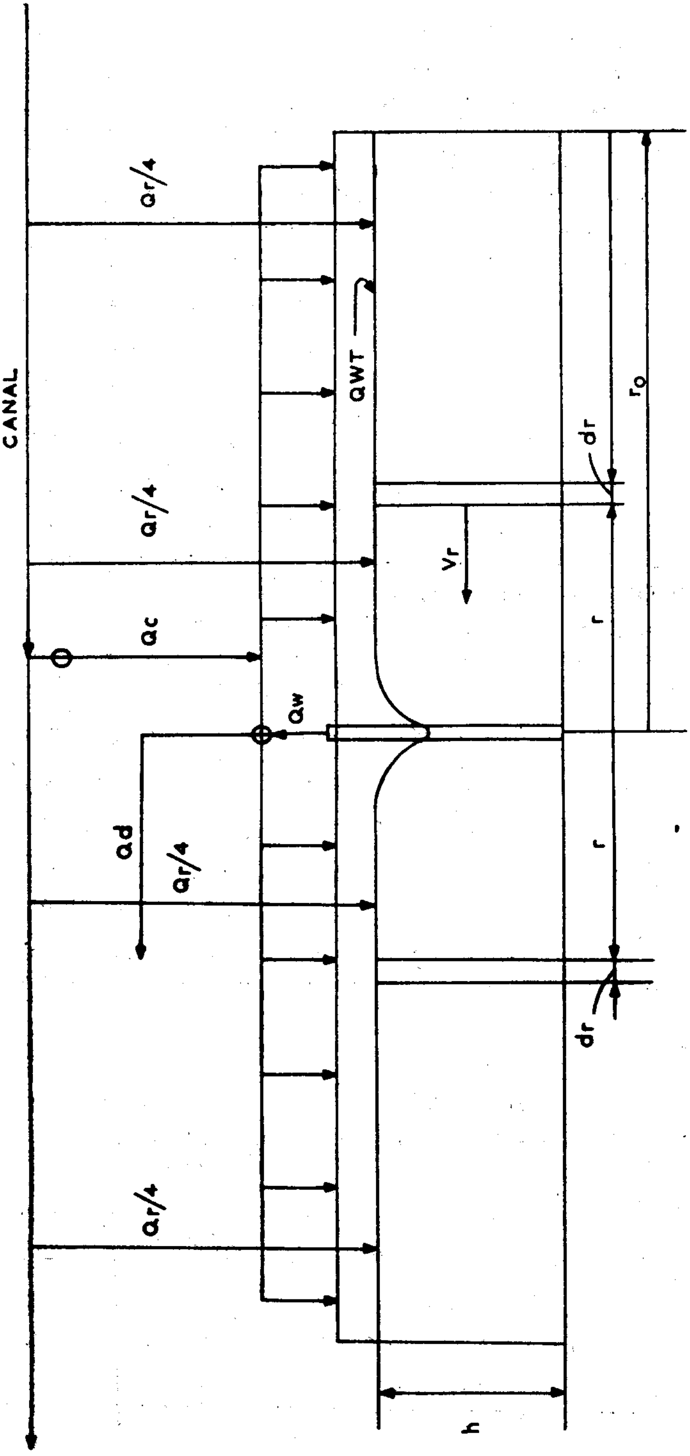
II. INITIAL GROUNDWATER SALINITY = 750 PPM
FINAL GROUNDWATER SALINITY = 1500 PPM

Well depth Feet	Soil salt, tons/acre	0	10	20	30	40	50
		Time in years to reach 1500 ppm in groundwater					
50		11.3	2.5	0	0	0	0
100		22.7	13.8	5.0	0	0	0
150		34.1	25.2	16.4	7.5	0	0
200		45.4	36.4	27.6	18.7	10.0	0.9
250		56.7	48.0	39.2	30.4	21.6	12.5

TABLE VII

SALINITY OF TUBEWELL WATER AT DIFFERENT TIMES, WHEN DRAINAGE SYSTEM IS INSTALLED AT THE BEGINNING OF PUMPING

Time in years	0	10	20	40	50	100	200	250
	Salinity, ppm							
Well depth, 100 feet	750	870	975	1165	1230	1540	1830	1895
Well depth, 250 feet	750	800	850	935	975	1165	1435	1540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