Waterlogging and Salinity in the Indus Plain: A Critical Analysis of Some of the Major Conclusions of the Revelle Report

by

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INTRODUCTION

In September 1962, President Kennedy's Science Advisory Committee, headed by Dr. Roger Revelle, then Science Adviser to the United States Secretary of Interior, submitted its *Draft Report on Waterlogging and Salinity in West Pakistan* [31]. An analysis of the main recommendations of this report was published in an earlier issue of this *Review* [9, pp. 251-279]. Much material was presented in that review which will not be repeated here.

The draft was considerably modified and final version of the report was prepared in January 1964 after a number of visits by Dr. Revelle and his colleagues to Pakistan [44]. The report was conveyed to President Mohammad Ayub Khan of Pakistan by President Lyndon B. Johnson of the United States with his letter of March 25, 1964. This article analyses the major recommendations of the final *Revelle Report* and argues that the solution presented in the *Revelle Report* is *i*) exceedingly costly compared to feasible alternatives, and *ii*) is not likely to bring about the necessary increases in agricultural production assumed in the *Revelle Report*. We argue that, on the basis of the evidence now available, far greater increases in agricultural production can be realized at significantly lower cost than those recommended in the *Revelle Report* by alternative methods of land and water development. These alternatives are presented in Section III of this article.

Background to the Revelle Report

The soils of the Indus Plain are alluvial. As is true of most alluvial valleys in arid climates, salts were deposited in varying degrees when the alluvium was laid. The low rainfall in the area has not been sufficient to leach these salts. Many of the irrigated lands also contain calcium carbonate nodules (locally termed as *kankar*) in the surface profile. These appear to have been formed since irrigation was introduced in the Plain.

Construction of perennial[1] canals in the Punjab was started in the latter part of the nineteenth century; and by 1915, the major part of the presently irrigated area had been covered with a close network of canals. Due to con-

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tinuous seepage of water from these canals, their branches, distributories and watercourses, the watertable has been rising at an average rate of about one to one-and-a-half feet a year so that by 1940 it had come to within ten to fifteen feet of the ground surface in the major part of the perennially irrigated areas. Since then, the watertable has been rising but at a slower rate.

Irrigation practices have also contributed to salt accumulation. One cusec[2] of water is generally supplied for 333 acres in West Pakistan compared with one hundred acres or less in the western part of the United States and other countries under similar climatic conditions. Water applied is, thus, less than the evapotranspiration requirements of crops; hence, the water does not wash down much beneath the rootzone, and salts are left behind in the upper surface of the soil. Because of the remarkably low salt content of the canal waters, this practice does not do much harm in a few years; but over many decades it leads to damaging salt accumulation.

More serious is the capillary rise and evaporation of the underground water that occurs when the watertable comes to within ten feet of the ground surface. The salts left behind by evaporation are deposited on the fields and within a few years the salt content of the soil builds up to a level that retards and ultimately prevents crop growth.

Many attempts have been made in the past to reclaim salty and waterlogged lands. Among the various measures tried were lining of selected reaches of canals, lowering of the level of water in the canals, closure of canals in the winter, and construction of drains in severely affected localities. In 1918, eighty miles of main drains were dug. In 1925, an area of 3,600 acres, which had been abandoned due to the rise of the watertable and salinity, was selected on the Lower Chenab Canal (at a place called Charkanwali), and various system of drains were tried. Open field-drains and open collector-drains were found to be more beneficial and economical than other types of drains. The whole area was reclaimed in a few years and all crops began to be grown [26, p. 189].

As a result of the recommendations of E. Mackenzie Taylor and his co-workers, construction of open shallow-drains for removal of monsoon rainwater was started in 1933 [34]. This was based on the conclusion that the main cause of the rise in watertable was the monsoon rainfall. By 1947, about 2,300 miles of drains had been constructed in the Rechna and Chaj *Doabs*[3].

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1 Canals which supply water to land throughout the year and are fed from a permanent barrage or diversion dam spanning the source-river are called perennial canals.

2 Cusec means one cubic foot per second. It is the most commonly used measure of irigation watersupply in West Pakistan. One cusec of water used for one year will deliver 720 acre-feet of water.

3 The term *doab* refers to an area of land located between two rivers.

In 1954, a detailed investigation of the problem was started by the Irrigation Department, Punjab, and later by the West Pakistan Water and Power Development Authority (WAPDA), with the help of the International Cooperation Administration[4]. This effort, along with work carried out between 1954 and 1959, culminated in the preparation of the Salinity Control and Reclamation Project Number One (SCARP 1) in the Rechna *Doab* [40].

In order to make a detailed investigation of the waterlogging and salinity problem throughout the province, the West Pakistan WAPDA, in 1959, appointed two firms of consultants, namely, Hunting Technical Services Limited (for work in the Southern Zone) and Tipton and Kalmbach, Inc. (for work in Northern Zone). A number of detailed reports had been prepared or were under preparation by these consultants [15, 16, 17, 36, and 37], when in 1961, the President of Pakistan called a meeting to consider measures to cope with the problem. At this meeting, the President requested a Masterplan for the control of salinity and waterlogging in West Pakistan. Drawing upon the extensive studies which had been going on for many years, the West Pakistan WAPDA produced such a plan in May 1961 [41]. This plan called for construction of 31,000 tubewells, 7,500 miles of major drainage-canals and 25,000 miles of supplementary drains at a total cost of rupees 5,900 million. The entire irrigated area of West Pakistan was to be divided into twenty-six project areas of different sizes for waterlogging and salinity control. The first project under this plan, SCARP 1 in Rechna *Doab*, went into operation in 1960/61.

The WAPDA Masterplan was discussed by President Mohammad Ayub Khan during his state visit to the United States in 1961 with President John F. Kennedy. As a result of this discussion, President Kennedy assembled a Panel of experts composed of specialists in agriculture, soil science, hydrology, geology, engineering and social sciences under the chairmanship of Dr. Roger Revelle, the then Science Adviser to the Secretary of Interior. They submitted a draft report in September 1962 [31] and the final report (referred to hereafter as the *Revelle Report*) in January 1964 [44].

In Section II of this paper, we summarize the major recommendations of the *Revelle Report*. In Section III we give our comments on these recommendations and offer some alternatives for land and water development for policy reorientation.

II: MAJOR RECOMMENDATIONS OF THE REVELLE REPORT

The *Revelle Report* starts with the assumption that waterlogging and salinity is destroying the fertility of much of the irrigated area of West Pakistan; however, this is seen as only one of the problems besetting the agriculture in the

[4] Now the Agency for International Development (AID).

Indus Plain. Among the other deficiencies cited are shortage of irrigation water, the system of land holdings, primitive methods of cultivation, lack of credit and marketing facilities, and inadequate transport and supporting technical services in the rural areas. The *Revelle Report,* therefore, recommends an integrated programme for the provision of additional watersupply and drainage by tubewells, use of more fertilizer, pure seed of improved varieties of crops, pest and disease control and better cultural practices.

The total irrigated area in the Indus Plain is twenty-three million acres, for which an average of seventy-four million acre-feet[5] (MAF) of water was annually diverted into canals during the five years ending 1956/57. Because of conveyance and application losses, only thirty-four to forty-one MAF of water is available for crop use. Consequently, an average of 1.5 to 1.8 acre-feet per acre of canal water has been available for crops.

The average annual diversion of water at canal heads is expected to increase from the eighty MAF a year that can be obtained with the construction of new barrages and link canals of the Indus Settlement Plan, to about ninety-two MAF a year after the construction of Mangla and Tarbela Dams. Out of this, about forty-eight MAF a year will go to the Punjab and Bahawalpur canals and about forty-four MAF a year to Sind canals. Out of forty-eight MAF of average diversion in the Punjab and Bahawalpur, the watersupply actually available for corps is estimated at 24.3 MAF a year—the balance being lost by nonbeneficial evapotranspiration and leakage from canals and branches [44, pp. 270-71].

Recharge of groundwater in the Punjab and Bahawalpur is estimated as follows:

a) Leakage from canals and branches	13.9 MAF
b) Seepage from rivers	2.0 MAF
c) Seepage from rainfall	1.0 MAF
d) Seepage from link canals	3.1 MAF
Total ...	20.0 MAF

The *Revelle Report* also makes the basic assumption that out of thirty million acres of land in the Punjab and Bahawalpur, twenty-three million acres have nonsaline groundwater containing an average of 700 parts per million (p.p.m.) of dissolved salts and the remaining seven million acres have saline groundwater with an average of 6,000 p.p.m. of dissolved salts [44, pp. 281-82][6].

[5] One acre-foot is the amount of water required to cover one acre to a depth of one foot. It is the most commonly used measure of irrigation watersupply.

[6] In the *Draft Revelle Report* of September 1962, the area having nonsaline groundwater was estimated as nineteen million acres and that having saline groundwaters was estimated as nine million acres. In the *Final Revelle Report* the extent of saline groundwater areas has been decreased and that of nonsaline groundwater areas has been increased. No reason for this change has been given in the *Final Revelle Report.*

Tubewell Installation

The *Revelle Report* proposes that the groundwater be pumped extensively *i*) to capture the whole of the recharge and *ii*) to mine the aquifer so as to lower the watertable by one hundred feet in thirty years in the nonsaline areas and by fifty feet in the saline areas [44, p. 273].

The amount of water to be pumped is estimated at 40.6 MAF a year in the nonsaline area and 8.9 MAF a year in the saline area or a total of 49.5 MAF a year [44, p. 281][7]. When this amount is added to the canal water-supply of 24.3 MAF at the outlet head, the total water will become 73.8 MAF a year. Out of this about 15 per cent or eleven MAF will be recycled[8] and 3.9 MAF of highly saline water will be exported out of the area. The remaining fifty-nine MAF will be available for use by crops. The net acreage that would be cultivated in the Punjab and Bahawalpur would amount to 16.4 million acres[9] of which 13.6 million acres would lie in the nonsaline area and 2.8 million acres would be in the saline area. The average depth of water will be 3.5 acre-feet per acre in the nonsaline area and 4.0 acre-feet per acre in the saline areas.

Modification of the canal system to transport an increased volume of river water for long distances into areas overlying salty underground water is not considered economical by the Revelle Panel. Even without such an additional supply of canal water, it is believed that the average salinity of irrigation water in the saline areas can be held as between 1,200 and 2,000 parts per million [44, p.14].

Tubewells will be installed in the whole of the thirty million acres; 56 per cent of the pumps would lie within the cultivated area, whereas 44 per cent would lie in the uncultivated area [44, p. 322][10].

Salinity of groundwater will increase when the salts present in the soil are washed downward. Moreover, there is an influx of salt from the canal water. To maintain the salt balance[11] at a satisfactory level for agriculture, about

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7 In the *Draft Revelle Report* f September 1962, the amount of water to be pumped was estimated at 34.6 MAF a year in the nonsaline area and 11.4 MAF a year in the saline area, or a total of 46.0 MAF a year.

8 The term recycling means that this amount of water after being pumped out will again seep down into the groundwater aquifer.

9 In the *Draft Revelle Report* the total area to be irrigated in the Punjab and Bahawalpur was estimated at 15.4 million acres of which the area actually irrigated at that time was 14.1 million acres.

10 In the *Draft Revelle Report* tubewells were proposed to be installed only inside the canal-irrigated areas and not in the uncultivated areas.

11 The term salt balance concerns the ratio between the quantity of dissolved salts in the irrigation water delivered to an area and the quantity removed from the area by drainage. If irrigated areas are to be kept in continuous production, the outflow of salts must equal or exceed the inflow.

10 per cent of the total water used for irrigation will eventually have to be exported. However, it is stated that for the next ten or even twenty years, the amount of water to be exported does not need to be more than one million acre-feet a year[12] [44, p. 305].

Out of forty-four MAF of canal water available for the Sind, about eleven MAF a year may be lost by canal and watercourse leakage; about six MAF a year by nonbeneficial evapotranspiration. Around twenty-seven MAF a year will be available for consumptive use of crops. About four to twelve MAF a year can be obtained by pumping from tubewells near the Indus. The total water available for crops will, thus, be about thirty-one to thirty-nine MAF a year. At the rate of three-and-one-half to four acre-feet per acre, this would cover a maximum of eight to eleven million acres. This is more than the present cultivated area but less than the twelve million acres under the canal commands [44, pp. 283-285].

Surface and Subsurface Drainage

The *Revelle Report* states that surface and subsurface drains are used in controlling the watertable and the build-up of salinity in many agricultural regions elsewhere in the world. It would be possible to use them on the Indus Plain in place of tubewells. In the Punjab, however, the *Revelle Report* states that according to the Panel's calculations, such horizontal drains are not only much more expensive than tubewells for eliminating waterlogging and salinity, but they do not provide the outstanding advantages of the latter, namely, the increase and regulation of the irrigation watersupply[13]. The *Revelle Report* merely acknowledges that in parts of Sind and a few other places where vertical drainage by tubewells may not be practicable, recourse must be had to horizontal drainage by surface and subsurface drains [44, p. 269]. In the major part of Sind, however, tubewells will be installed and water pumped into conveyance channels to return saline water to the Indus [44, p. 325].

Capital Cost

The capital cost for installation of tubewells and for other agricultural development in the Punjab and Bahawalpur is estimated at eighty-one million dollars, or 385 million rupees for each project area of one million

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[12] At another place the *Revelle Report* says that for the next *twenty* or *thirty* years the amount of water to be exported does not need to be more than a million acre-feet per year [44, p. 14].

[13] No details of the calculations showing that the drains are more expensive than tubewells are given anywhere in the *Revelle Report*.

acres[14]. The major components of this cost are shown in Table I. For Sind, the capital cost is estimated at 100 to 110 million dollars for each project area[15].

TABLE I

CAPITAL COST OF LAND AND WATER DEVELOPMENT FOR ONE MILLION ACRES IN THE PUNJAB AND BAHAWALPUR

Components of cost	million dollars	million rupees
Tubewells and their electrification	41.0	195
Drainage system (return flows and floods)	5.0	24
Salt export system (wells for pumping salt water *plus* conveyance channels)	6.6	31
Transporting pumped water from uncultivated area to cultivated areas or its equivalent	9.1	43
Subtotal : tubewells and drains	61.7	294
Fertilizer plant and distribution facilities	12.0	57
Pest control and seed treatment	2.0	10
Facilities for education, research, extension and management	5.0	24
Total	80.7	385

Source: [44, p. 165, Table 3.4].

The estimated cost is higher for Sind because a grid of conveyance channels must be constructed to carry off saline pumped waters and canal capacity must be enlarged to bring in additional water [44, p. 11].

[14] In the *Draft Revelle Report*, the capital cost for each project area was estimated at 54.5 million dollars or 260 million rupees, as follows:

	(*million dollars*)
Wells and electrification	20.0
Power	12.5
Drainage and redistribution	5.0
Fertilizer plant	10.0
Pest control and seed treatment	2.0
Education, research, extension	5.0
	54.5

The major difference in the *Final Revelle Report* is in provision for drainage and redistribution, which has been increased from 5.0 million dollars in the *Draft Report* to 20.7 million dollars in the *Final Report*. The cost of tubewells has also been increased by 8.5 million dollars.

[15] At another place in the Report, the cost of a project area in Sind is given as 110 to 150 million dollars [44, p. 142].

Total capital cost for 16.4 million acres in Punjab and Bahawalpur and 9 to 10 project areas in Sind would be 2.3 billion dollars or 11 billion rupees [44, p. 11]. Exclusive of the fertilizer, plant protection, and improved seed, the cost would be 8.5 billion rupees.

Annual Cost

The annual operating cost per net cultivated area is estimated at 107 rupees per acre out of which 55 rupees will be required for running cost of the tubewells; the remaining 52 rupees are allocated for fertilizer and other agricultural-improvement facilities[16].

Benefits

The present value of crops in a " typical " million-acre tract in the Lower Chenab Canal area of the Punjab is estimated at 152 million rupees. With the installation of tubewells, more than two MAF of water is expected to be available for each project area. This is expected to result in a gross increase of 236 million rupees[17] and net increase of 204 million rupees in the value of agricultural production as shown in Table II. The difference between gross value

TABLE II

EXPECTED INCREASE IN PRODUCTION FROM INCREASED USE OF TUBEWELL WATER AND AGRICULTURAL MODERNIZATION IN MILLION-ACRE TRACT IN THE LOWER-CHENAB-CANAL AREA

Source of increased production	Gross value	Net value
	(million rupees)	
Increased depth of water on present crops	8	8
Desalination and reclamation	43	43
Increased gross crop acreage	79	73
Nitrogen fertilizer	62	44
Improved seed and plant protection	44	36
Total potential increase	236	204
Present value	152	142
Total potential value	388	346

Source: [44, Table 5.10].

16 In the *Draft Revelle Report*, when the tubewells were located inside the cultivated area only, the operating annual cost was estimated at fifty-five rupees per acre, out of which seventeen rupees were estimated for operation of tubewells and thirty-eight rupees for fertilizer and other agricultural improvement facilities.

17 In the *Draft Revelle Report*, the gross increase was estimated at 256 million rupees and net increase as 215 million rupees in the value of agricultural production in each project area.

and net value is small because the tillage costs are considered to be minor. It is stated that "they comprise, principally, four elements. (1) Rental value of additional land cultivated. This can be neglected since it is not a social cost, the land would be simply unused and useless without the additional water. (2) Additional labour for cultivation. . . . There is a considerable surplus of farm labour which can be applied to land without sacrificing valuable output elsewhere. (3) Additional labour of draft animals. . . . even after taking into account the need for more bullock feed, the value of milk and meat production for the fodder and straw grown on the additional acreage would be . . . above the cash value of total new fodder production. (4) Additional expense for purchase of fertilizer, seed, plant protection and other agricultural requisites. Under current methods of tillage these costs appear to be nominal except for a few crops such as sugarcane. . . . It will undoubtedly be necessary to fertilize most of the new land brought under cultivations, but this will also produce additional benefits" [44, p. 193].

The Report sets the value of present crops at 203 rupees per net cultivated acre. This will rise to a predicted 471 rupees per acre, an increase of 126 per cent over the existing value, after the installation of tubewells and agricultural modernization programme.

Total value of crops in the irrigated areas of the Punjab and Bahawalpur in 1960 was 2,400 million rupees on 15.4 million acres of net area sown. When the net area sown increases to 16.4 million acres, and the value of crops by 126 per cent on each acre sown, the total value of production could rise to 5,600 million rupees after the installation of tubewells and modernization of agriculture [44, p. 201].

The Revelle Panel estimates that if tubewells are used for the recovery of recharge water only, with the watertable under the well fields held at an average of fifty feet, the capital costs would be 57 per cent of the design in which the groundwater is mined to 110 feet in thirty years. Operating costs would also be 57 per cent of those in the latter case. However, by mining the groundwater it is, the Panel members conclude, possible to add 4.8 million acres to the cultivated area. According to the Report, the net benefits of mining, discounted to the present time, more than offset the discounted additional costs involved [44, pp. 323-325].

Organization

The *Revelle Report* states that although the purely technical possibilities for the improvement of agriculture in Pakistan are fabulous, there are organizational and intangible impediments which must be overcome in order to realize the increases in agricultural production. These impediments are mobilization and motivation of governmental personnel, need for better guidance and education of the farmers, improved marketing facilities, improved agricultural credit and continued land reforms [44, p. 201].

The *Revelle Report*, therefore, recommends a reorientation of strategy to concentrate efforts on limited project areas. It recommends that the major part of the irrigated area of the Indus Plain be divided into some twenty-five to thirty project areas of roughly one million acres, each manned by a competent and adequate staff under the supervision of a Project Director. At the provincial level, a Land and Water Development Board is recommended for getting approval of the government for development of various areas and to coordinate the work of various departments in the project areas. The *Revelle Report* recommends that the Project Director should have authority to *supervise* and *direct* the project personnel and not merely to *coordinate* their activities. A large staff is recommended for each project area consisting of 60 senior administrative and technical men, about 300 junior staff and about 1900 foremen, technicians, clerks and labourers [44, p. 164]. It is stated that the operating expenditure of the development organization will be high throughout the Revelle-Plan period and that cost of these, for the first few years, should be regarded as capital expenses [44, p. 158].

III: COMMENTS ON THE REVELLE REPORT AND SOME SUGGESTED ALTERNATIVES FOR POLICY ORIENTATION

The major recommendation of the Revelle Panel is that tubewells be installed in the whole of the Indus Plain. The Panel recommends that tubewell waters be used for crop production in the whole of the Punjab and Bahawalpur, both in the nonsaline and in the saline groundwater areas. The Panel further proposes that in Sind, part of the saline pumped water be used for crop production, but that the major part of the tubewell water be pumped into conveyance channels and be disposed of in the Indus river. The Panel further recommends that the project directors of twenty-five to thirty project areas into which the Indus Plain is to be divided should have responsibility for modernizing the agriculture of their project areas and that they should have a large and competent staff for this purpose.

We consider that most of the recommendations of the Revelle Panel are questionable on technical as well as economic grounds. A summary of our comments on the major recommendations of the *Revelle Report* and some of the alternatives suggested by us is given below.

A. SUMMARY OF THE CONCLUSIONS OF THIS PAPER

1) Development of Nonsaline Areas

The Revelle Panel has considered the quality of irrigation water mainly on the basis of total salt content. The only mention of sodium in the Punjab and Bahawalpur groundwaters is contained in the assumption that one-third of the tubewells have an effluent with an excessive salinity or sodium absorption ratio such that they require dilution with surface water in the ratio of 1:1. No mention is made of the excessive bicarbonate found in the groundwaters. An examination of tubewell waters in the Punjab and Bahawalpur and in SCARP-1 area indicates that many of the groundwaters considered as fit for irrigation by the Revelle Panel have excessive amounts of sodium and an unfavourable ratio between calcium *plus* magnesium and bicarbonates. Use of such water would cause the soils to become impermeable and alkaline. Such waters can be used for irrigation only by mixing it with large quantities of canal water or with heavy applications of gypsum[18] and heavy drainage rates to prevent eventual development of high alkalinity. Canal water is not likely to be available in adequate supply to mix with all of the groundwaters; and the cost of the necessary gypsum added on to the heavy cost of pumping would make the use of such waters uneconomic. In the long run, there would, therefore, be a decrease in crop production rather than an increase with the use of such waters. We, therefore, recommend that tubewells should not be installed all over the Punjab and Bahawalpur but only in such areas where the sodium content and the bicarbonates in relation to calcium *plus* magnesium content are low so that the use of such waters does not cause the soils to become impermeable and alkaline.

2) Development of Saline Areas

For areas where groundwaters are saline, and contain excessive sodium, deep open-surface drains would be better than tubewells for eliminating waterlogging and salinity. The deep open-surface drains can be supplemented with open and/or tile-field drains to remove the excess of water and salts from the waterlogged and saline soils. Such deep open-main drains with open and/or tile-field drains are a common feature of almost all irrigation projects in the United States, the Soviet Union, and Egypt. Provision of these drains along with an appropriate increase in the canal water to these areas would result in far greater increases in agricultural production than is possible by the pumping and use of saline groundwaters.

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[18] Gypsum is hydrated calcium sulphate. When applied to the soil containing high sodium content, it reacts to form the less harmful and more soluble sodium sulphate and lime, a desirable soil constituent.

3) Private Tubewells

In nonsaline areas, where tubewells are to be installed, the main objective should be to supply additional irrigation water for crop use. Drainage in these areas becomes of secondary importance when the watertable is lowered. Such tubewells are being installed privately by the farmers in the Punjab and Bahawalpur at a much lower cost than the tubewells installed by the government in Salinity Control and Reclamation Projects. Based on experience to-date, additional area brought under crops and the increase in agricultural production are much higher in areas where tubewells are being installed privately by the farmers than they are in the areas where these are installed by the government. This would seem to indicate a policy of maximum assistance to farmers for installation of private tubewells. Instead of planning the whole reclamation-and-salinity control programme in the public sector, the government should concentrate on providing electric-transmission and special credit facilities in the nonsaline areas so that tubewells can be installed by the farmers.

4) Construction of Drains

While the farmers are themselves able to install tubewells with the help of private drilling-concerns, they need considerable technical assistance in the layout of field drains, whether open or covered. This assistance will have to be provided by the government in areas in which field drains are required. In addition, all collector drains and deep main drains will have to be dug by the government. Most of these can be dug by hand-labour under the Rural Works Programme at a very low real cost to the economy.

In the following sections, we give our detailed comments on major recommendations of the *Revelle Report* and expand upon alternative proposals for elimination of waterlogging and salinity and for increasing agricultural production in West Pakistan.

B: CHEMICAL COMPOSITION OF GROUNDWATER

1) Quality of Water and Tubewells

Suitability of pumped water for irrigation depends upon four factors [33, pp. 69-82]:

i) total concentration of soluble salts;

ii) sodium concentration in relation to calcium *plus* magnesium concentration;

iii) carbonate and bicarbonate concentration;

iv) boron concentration.

i) Total Salt Concentration: The total salt concentration is usually expressed in terms of electrical conductivity[19] (E.C.) as part per million (p.p.m.) of dissolved salts or as milliequivalent per litre[20] (m.e/1) of dissolved salts. According to the United States Salinity Laboratory (USSL) at Riverside in California, irrigation waters with electrical conductivity of less than 250 micromhos per cm at 25°C or less, that is, with less than 160 p.p.m. of dissolved salts are considered as excellent. Those waters with electrical conductivity of 250 to 750 (*i.e.*, 160 to 480 p.p.m. of dissolved salts) can be used if a moderate amount of leaching occurs. With these waters, plants with moderate salt tolerance can be grown without special practices for salinity control. High-salinity water having electrical conductivity of 750 to 2,250 micromhos per cm (480 to 1,440 p.p.m. of dissolved salts) cannot be employed on soils of poor drainage while waters of very high salinity (more than 2,250 micromhos per cm or 1,440 p.p.m. of dissolved salts) are not suitable for irrigation under ordinary conditions. These can only be used with very salt-tolerant crops and a high degree of leaching.

ii) Sodium: Sodium percentage of water is another important index of its quality. High sodium-content adversely affects the physical properties of the soil, makes the soil difficult to irrigate, and reduces the crop yields. The permissible sodium concentration depends upon the relative concentration of calcium and magnesium. The sodium hazard of irrigation water is usually expressed in terms of sodium-absorption ratio (SAR)[21].

In practice, total-salinity and sodium-absorption ratio must both be appraised, because the limits of sodium hazard are affected by total salinity.

iii) Carbonates and Bicarbonates: Carbonates and bicarbonates affect the soils in an indirect way. They cause precipitation of dissolved calcium and magnesium which increases the relative concentration of sodium. To evaluate the effect of carbonate and bicarbonate, the concept of 'residual sodium carbonate' is used[22].

19 Electrical conductivity is measured by the capacity of ionized inorganic salts in water solution to conduct an electrical current and is expressed in terms of specific conductance of water.

20 Milliequivalent is one-thousandth of an equivalent. Equivalent is the weight in grams of an ion or compound that combines with or replaces one gram of hydrogen.

Milliequivalent per liter (m.e/1) is one-thousandth equivalent weight of an ion or salt per one million gram of solution or soil.

21 Sodium-absorption ratio expresses the relative activity of sodium ions in exchange reactions with the soil. It is calculated from the following equation:

$$\text{SAR} = \frac{\text{Sodium ions}}{\sqrt{\dfrac{\text{Calcium} + \text{Magnesium ions}}{2}}}$$

22 Residual sodium carbonate is defined as the milliequivalent of carbonate and bicarbonate ions per litre of water remaining after the m.e/1 of calcium and magnesium are subtracted from m.e/1 of carbonates and bicarbonates in the irrigation water. If this calculation results in a negative value, the water is said to be free from residual sodium carbonate.

It is generally accepted that water with more than 2.5 m.e/1 of residual sodium carbonate are not suitable for irrigation, waters containing 1.25 to 2.5 m.e/1 are considered marginal and those containing less than 1.25 m.e/1 of residual sodium carbonate are considered as safe.

In evaluating the sodium hazards of groundwaters having high amounts of carbonates but no residual sodium carbonate, Dr. C. A. Bower, Director of the United States Salinity Laboratory at Riverside, California, has proposed the use of the concept of calculated 'exchangeable sodium percentage' (ESP)[23]. He considers that waters for which calculated ESP is less than 10 are probably safe for direct use, those for which the calculated ESP ranges between 10 and 20 may be considered as marginal, and those for which the calculated ESP exceeds 20 are definitely hazardous unless diluted with sufficient water to decrease the calculated ESP to less than 20 [3, p. 59].

2) Composition of the Punjab and Bahawalpur Groundwaters

The Water and Soils Investigation Division (WASID) of WAPDA nas, with the help of technical experts of the United States Geological Survey, carried out 2,600 complete chemical analyses of water samples from 800 test holes drilled between 1955 and 1962 [10, pp. 50-65]. Results of these studies are summarized below:

a) Total Salt Concentration: According to the analysis carried out by WASID of WAPDA, the salt content of the groundwater varies in different parts of the Punjab and Bahawalpur. The differences are largely due to the pattern of circulation that existed prior to the introduction of canal irrigation. At that time, groundwater moved from the rivers, and from upstream areas where precipitation was a factor of recharge, downstream into areas of progressively diminishing precipitation towards the south-western parts of the *doabs* where stagnation and discharge through evaporation were the dominant factors in the regime. With increasing distance from the areas of recharge and active circulation, groundwater in transient storage became progressively more mineralized. In areas of more or less active recharge and circulation, the mineral content increased gradually from less than 500 p.p.m. down the gradient to about 2,000 p.p.m. chiefly as a result of solution of material from the sediments. This trend gave way in the central and lower parts of the *doabs* to a rather abrupt transition* into zones of highly mineralized groundwater where the mineral content was enhanced by the effects of stagnation and evaporation from the watertable. The

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[23] The calculated ESP of an irrigation water is claimed to be the equilibrium exchangeable sodium percentage that will be attained by a soil irrigated with the water.

concentration of groundwater increased to about 20,000 p.p.m. in the lower reaches of Chaj and Rechna *Doabs* and Bahawalpur and to about 10,000 p.p.m. in the lower reaches of the Bari and Thal *Doabs* [10, pp. 52-53].

Harza Engineering Company have tabulated the aerial extent of the Punjab and Bahawalpur areas having different concentrations of salt. Their results are given in Table III. Of the thirty-four million acres of gross area in the

TABLE III

GROUNDWATER SALINITY IN THE PUNJAB AND BAHAWALPUR

Salinity concentration in parts per million	Gross area in million acres	Percentage of the total area
Below 500	10.7	31
500-1000	9.5	28
1000-3000	6.8	20
More than 3000	5.1	15
Unknown	1.9	6
Total	34.0	100

Source: [13, p. 37].

Punjab and Bahawalpur, nearly four million acres are located in the Thal desert and in the Bahawalpur desert. Out of the remaining thirty million acres, twenty-three million acres have groundwaters with less than 3,000 p.p.m. of dissolved salts and seven million acres have groundwaters with more than 3,000 p.p.m. of dissolved salts. It seems that areas with less than 3,000 p.p.m. of dissolved solids are regarded as nonsaline areas by the Revelle Panel.

We will later revert to this and show that this assumption by the Panel is not correct, particularly when chemical composition of the groundwaters is considered along with the total salt content.

b) *Chemical Composition*: The chemical composition of the Punjab and Bahawalpur groundwaters as determined by WASID of WAPDA is given in Table IV. It is only in groundwaters with less than 500 p.p.m. of dissolved solids

TABLE IV

COMMON RANGES OF THE PRINCIPAL CATION AND ANION CONCENTRATIONS IN THE NATIVE GROUNDWATERS

Doab	Total dissolved solids	CATIONS[a]			ANIONS[a]		
		Calcium	Magnesium	Sodium and Potassium	Carbonate and Bicarbonate	Sulphate	Chloride
	(p. p. m.)	(........	....	per cent	....	....	........)
Thal	Below 500	30—45	15—30	40—50	40—70	10—25	15—25
	1000—3000	11—20	10—25	65—85	5—20	25—50	40—70
	Above 4000	10—20	10—30	50—85	0—5	10—28	60—80
Chaj	Below 500	25—40	20—45	50—75	60—70	5—15	10—20
	1000—3000	3—20	10—26	60—80	30—55	20—50	25—40
	Above 4000	5—10	10—20	70—85	6—10	5—25	75—90
Rechna	Below 500	20—50	20—40	40—70	50—70	10—25	10—20
	1000—3000	4—20	6—25	60—85	20—56	25—40	20—60
	Above 4000	2—25	2—35	45—95	1—3	18—35	65—80
Bari	Below 500	16—35	15—30	45—65	50—65	25—40	6—15
	1000—3000	5—20	10—25	70—90	20—35	35—60	22—40
	Above 4000	10—25	15—25	50—80	6—10	20—40	50—75
Bahawalpur	Below 500	20—35	30—40	30—40	50—65	20—35	8—15
	1000—3000	8—20	11—25	65—80	15—30	35—65	15—40
	Above 4000	12—15	20—30	50—70	1—5	16—35	60—80

Source: [10, p. 62].

a) The principal salt constituents of the irrigation water are considered to exist in solution as electrolytes or dissociated ions. Some ions are basic and are called cations; others are acid and are called anions. When common salt, sodium chloride, is dissolved in water it supplies sodium ions as cations and chloride ions as anions.

that concentration of calcium and magnesium equals or exceeds the concentration of sodium. All other groundwaters have an undesirably high concentration of sodium. On this basis groundwaters with less than 500 p.p.m. of dissolved solids should be safe for direct irrigation use. However, these waters have an excessive proportion of bicarbonates. This is because the river water, which is of the calcium-bicarbonate type, upon entering groundwater circulation, gradually becomes more mineralized and is modified to the sodium-bicarbonate type within a few miles from the rivers. An increase in sodium content is also common in progressively deeper water samples. The relative increase in sodium at the expense of calcium appears to be the result of base exchange in the clays of alluvium.

The transition in chemical quality downgradient is largely the result of chemical reaction between the groundwater and the soil particles. The increased concentration chiefly involves the accretion of more soluble constituents of the rock particles, that is, sodium and chlorides and sulphates. *Thus*, while the groundwater in the range of concentration of dissolved solids between 500 and 1,000 p.p.m. is generally a sodium-bicarbonate water, that with 1,000 to 2,000 p.p.m. may be of the mixed type having sodium bicarbonate, sodium chloride and sodium sulphate.

Sodium and chloride account for much of the increase in concentration for waters having 2,000 to 4,000 p.p.m of dissolved salts as the character of groundwater evolves from a mixed type to a sodium-chloride type. Increasing concentration of dissolved solids above 4,000 p.p.m. is marked by a further increase in the relative concentration of sodium and chloride and in many of the highly mineralized waters sodium chloride accounts for about 75 per cent or more of the total dissolved salts [10, pp. 61-65].

To sum up, practically all of the Punjab and Bahawalpur groundwaters have undesirably high concentrations of sodium and/or bicarbonate. When such waters are used for irrigation, carbonates in the irrigation water precipitate as calcium carbonates or *kankar* and this precipitation enhances the tendency of the soil to accumulate exchangeable sodium from the water. As exchangeable sodium accumulates, the alkalinity of the soil further increases, leading to further calcium precipitation and repetition of the above process. Ultimately complete deterioration of the soil occurs in time [3, pp. 50-60].

Tubewells should not, therefore, be installed in areas where concentration of sodium and/or bicarbonates are very high.

R. L. Hausenbuiller, M. A. Haque and Abdul Wahab of Agricultural College, Lyallpur determined the extent of exchangeable sodium accumulation with the use of high bicarbonate Punjab groundwaters both in the field and in the laboratory. They found that irrigation with four of the eleven groundwaters over a period of four or more years resulted in accumulation of excessive amounts of exchangeable sodium in the soil, and that the extent of sodium accumulation was highly correlated with the residual sodium carbonate content of the water. They further found that soil irrigated with waters containing no residual sodium carbonate may accumulate exchangeable sodium in excess of that predicted by the sodium absorption ratio (SAR) of the water. They suggested that considerable risk may be involved in irrigating with waters containing as little as 1.25 m.e/1 of residual sodium carbonate [14, pp. 357-364].

Dr. F. M. Eaton, an FAO soil-salinity expert, examined the analyses of tubewell waters taken at different depths by the Agricultural Engineer, Lyallpur. Dr. Eaton came to the conclusion that "practically all these groundwaters would require heavy drainage rates and heavy applications of gypsum to prevent eventual development of high alkalinity and black alkali". He concluded that the high cost of gypsum, imposed on the much greater cost of pumped water, would limit the possibilities of pumping as universally applicable means of increasing agricultural production in West Pakistan [5, pp. 15-16].

C. R. Maierhofer, Chief of the Drainage and Groundwater Engineering of the United States Bureau of Reclamation, after a visit to West Pakistan, considered that the chemical analysis of waters and the chemistry of the soils that had been irrigated for long periods indicated that the soluble sodium percentage and calcium-*plus*-magnesium ratio to bicarbonate in the water may not be favourable. Under such condition when groundwater is used to supplement the irrigation supply, calcium precipitates as carbonate in the form of nodules (*kankar*) and the soil solution becomes increasingly concentrated with sodium. These concentrations lead to complete deterioration to alkaline status in time [23, p. 17].

3) Chemical Composition of SCARP-1 Groundwaters

The Water and Soils Investigation Division of WAPDA is undertaking a chemical analysis of all SCARP-1 groundwaters. Harza Engineering Company and the United States Salinity Laboratory at Riverside in California have examined the chemical analyses of the groundwaters in the SCARP-1 area as determined by Water and Soils Investigation Division of WAPDA. The results of their examination are given in Tables V and VI.

TABLE V

ANALYSIS OF 729 TUBEWELL WATERS IN SALINITY CONTROL AND RECLAMATION PROJECT NUMBER ONE IN RECHNA *DOAB*

Total dissolved salts		Residual sodium carbonate	
Parts per million	Per cent of samples	Milliequivalents per litre	Per cent of samples
Less than 500	39	Zero or less	24
500-750	27	Zero to 2.5	37
More than 750	34	More than 2.5	39

Sourcc: [22, p. 153].

TABLE VI

ANALYSIS OF 74 TUBEWELL WATERS OF SCARP-1 AREA BASED ON RESIDUAL SODIUM CARBONATE AND CALCULATED EXCHANGEABLE SODIUM PERCENTAGE

Calculated exchangeable sodium percentage		Residual sodium carbonate	
Range of ESP	per cent of samples	Milliequivalents per litre	Per cent of samples
Less than 10 (safe)	32	Less than 1.25 (safe)	45
10-20 (marginal)	28	1.25—2.5 (marginal)	19
More than 20 (hazardous)	39	More than 2.5 (hazardous)	36

Source: [3, p. 59].

Using the traditional standard that waters with amounts of residual sodium carbonate exceeding 2.5 m.e/1 are hazardous for irrigation use, Maasland and his associates concluded that 39 per cent of the Rechna-*Doab* tubewells were hazardous for irrigation use (*see*, Table V). Using the new method evolved by the United States Salinity Laboratory at Riverside in California, Bower and Maasland also found that 39 per cent of SCARP-1 groundwaters were hazardous on the basis of calculated ESP. They concluded as follows: "If the 74 tubewell waters considered in this study are representative of a substantial fraction of the Punjab groundwaters, then by either the "residual Na_2CO_3" [sodium carbonate] concept or the empirical equation a potential sodium hazard is involved in the use of many of these waters for irrigation. It seems evident that if some of the groundwaters are used as the sole source of water for irrigation, the soil will accumulate injurious amounts of exchangeable Na [sodium] with time. On the other hand, if hazardous groundwater is used to supplement surface water for irrigation by dilution or by alternate use, no excessive accumulation of exchangeable Na may occur. Rainfall, where appreciable and effective, may also be expected to have a retarding effect on the accumulation of exchangeable Na from hazardous waters. It is evident that the Na hazard of the Punjab groundwaters needs further study with particular attention being given as to how surface waters, groundwaters, and soils can be managed so as to prevent harmful accumulations of exchangeable Na. In any case, changes in the ESP and permeability of soils over time resulting from the use of groundwaters of various qualities should be measured as a means of acquiring information on the Na hazard of the groundwaters." [3, p. 60].

For the seventy-four samples for which results are given in Table V, we have worked out the concentration of total dissolved salts in p.p.m. and compared this with the calculated ESP. We find that:

i) most of the waters which are safe for direct use on the basis of calculated exchangeable sodium percentage (ESP less than 10) have less than 500 p.p.m. of dissolved salts;

ii) most of the samples which are marginal on the basis of calculated exchangeable sodium percentage (ESP between 10 and 20) have 500 to 750 p.p.m. of dissolved salts;

iii) most of the samples which are hazardous on the basis of calculated exchangeable sodium percentage (ESP more than 20) have more than 750 p.p.m. of dissolved salts.

4) Classification of the Punjab and Bahawalpur Groundwaters

Accepting the classification of groundwaters on the basis of calculated ESP as evolved by the United States Salinity Laboratory at Riverside in California and the very close relationship found between ESP and total salt content in SCARP-1 groundwaters, we have classified the Punjab and Bahawalpur groundwaters on a rough basis. We have assumed that groundwaters containing less than 500 p.p.m. of dissolved solids or calculated ESP of less than 10 are likely to be fit for irrigation, those with 500 to 750 p.p.m. of dissolved salts or calculated ESP of 10-20 are likely to be marginal and those which have more than 750 p.p.m. of dissolved salts or calculated ESP of over 20 are likely to be hazardous for irrigation use.

Salinity of the Punjab and Bahawalpur groundwaters given in Table III shows that 31 per cent of the waters have less than 500 p.p.m. of dissolved salts and 28 per cent have 500 to 1,000 p.p.m. of dissolved salts. As an approximation, one-half of 28 per cent may be assumed to contain 500 to 750 p.p.m. of dissolved salts. Similarly, we will assume that one-half of the 6 per cent waters for which no chemical analysis is available contain 500 to 750 p.p.m. of dissolved salts. The Punjab and Bahawalpur groundwaters may be compared, on this rough and ready basis, with SCARP-1 groundwaters (Table VII). On the basis of total

TABLE VII

SALINITY OF THE PUNJAB AND BAHAWALPUR GROUNDWATERS COMPARED WITH SCARP-1 GROUNDWATERS

Salinity concentration	SCARP-1 groundwaters (1)	Punjab and Bahawalpur groundwaters (2)
(p.p.m.)	(.........*per cent*.........)	
Below 500	39	31
500-750	27	17
More than 750	34	52

Sources: Col (1): Table V.
Col (2): Table III and the text.

salt content, it appears that groundwaters over the Punjab and Bahawalpur as a whole are somewhat inferior to the groundwaters in SCARP-1 area. On the basis of chemical analysis of the Punjab and Bahawalpur groundwaters given in Table IV, it appears that the content of sodium and bicarbonate in relation to total salt content in the Punjab and Bahawalpur groundwaters is about the same as that of Rechna-*Doab* groundwaters. Therefore, about half of the Punjab and Bahawalpur groundwaters are likely to be hazardous for irrigation use on the basis of the calculated exchangeable sodium percentage[24]. About 17 per cent of them (*i.e.*, those containing 500-750 p.p.m. of dissolved salts) are likely to be marginal; but they could be used for irrigation when mixed with canal water

24 According to Harza Engineering Company, "it is unrealistic to assume that more than 60 per cent of the low salinity (so called "fresh") ground waters can be used safely for irrigation without dilution or mixed use" [13, p. II-23]

or with heavy applications of gypsum to the soil. Application of gypsum would be too costly for use with waters having excessive sodium and carbonate contents (even with waters having less than 750 p.p.m. of dissolved salts)[25]. All of these marginal waters should, therefore, be used in conjunction with canal water as is in fact being done by WAPDA and by the farmers of the Punjab and Bahawalpur.

There is some question regarding the exact correlation between salt content and ESP. Milton Fireman and M. A. Haque, who studied the effect of tubewell waters on soils in SCARP-1 area, stated: "It is interesting to note that the salt content of these waters increases with calculated ESP; therefore this index (ESP) also serves to group the waters on the basis of salinity" [7, p. 2]. On the other hand, V. E. Hansen, C. A. Bower and G. J. Williams, who examined the analytical data for Sind soils, found that ESP and salinity level of Sind soils tended to be positively correlated but the correlation was not sufficiently good to satisfactorily estimate the ESP from the salinity level. They concluded that an independent evaluation of ESP will, therefore, be needed [11, p. 35]. If the correlation between salt content and ESP in the Punjab and Bahawalpur groundwaters is not as strong as that in SCARP 1, it is possible that some of the waters having more than 750 p.p.m. of dissolved salts may not have so high an ESP as to preclude them from irrigation use. A part of the 17 per cent of groundwaters having salt content between 750 and 1,000 p.p.m. may be found to be fit for development. A detailed chemical analysis of the individual areas particularly with regard to bicarbonate and sodium should be carried out. Maps showing areas with high-sodium groundwaters and high-bicarbonate groundwaters should be prepared before tubewells are installed in areas having more than 750 p.p.m. of dissolved salts.

There is another reason why we should be very cautious in selecting areas for tubewell installation. Several factors will tend to deteriorate the quality of groundwater overtime. *First,* the leaching of soil profile will add appreciable amounts of salts to the groundwater in storage. *Secondly,* in the cycle of recirculation of water from aquifer to fields and back to the aquifer, most of the salts will remain in solution whereas most of the water will be lost to evaporation. *Thirdly,* there will be an annual increment of salts from canal water to the aquifer. *Finally,* chemical reaction between the percolating water and the sediments will bring more salt into solution [10, pp. 91-92]. The effects of these factors will be mitigated somewhat by dilution with recharge by seepage from

[25] *See,* for example, M. Maasland, C.E. Priest and M.S. Malik. They state: "It has been proposed to overcome the adverse effects of the high carbonate contents of tubewell waters by dissolving gypsum in the tubewell water or applying gypsum to the land. The former appears impractical because of the relatively low solubility of gypsum (30 m.e/l). Both appear infeasible in view of the high quantity of gypsum that is required". [22, p. 137].

canals, rivers and rainfall. But the quality will continue to deteriorate. Tubewells should, therefore, be installed only in areas where groundwaters have low salt-content, so that no great deterioration of pumped waters takes place overtime.

The Revelle Panel developed a mathematical model called the "Salt-Flow Model" for digital computor simulation and investigated the rate of increase of groundwater salinity with tubewell pumping. They found that with no initial salt on the ground surface the concentrations of applied irrigation water remained under 1,100 p.p.m. during the first fifty years. But with initial salt concentration of sixty tons per acre in the surface soil (average value for large area of saline soils in the Punjab and Bahawalpur), the concentration of applied irrigation water fell above the 1,100 p.p.m. level all or part of the time during the first fifty years. They concluded that surface drainage of about 10 per cent of the tubewell pumping over a 50-year period was needed to prevent eventual excessive salt accumulation in the rootzone of crops [44, pp. 301-306].

We have two comments on this. *First*, as pointed out by Maasland, Priest and Malik, if the watertable is lowered from 10 feet to 110 feet below ground surface with 250-foot tubewells, the salinity will increase approximately to $(250/150) \times 100 = 167$ per cent of that estimated by the Panel [22, p. 149]. Therefore, either a drainage rate of more than 10 per cent will have to be provided or the salinity of the mixed water will fall above 1,100 p.p.m. *Second*, the basic assumption by the Revelle Panel in the above "Salt-Flow Model" that concentration of mixed canal-and-tubewell water can be accepted as 1,100 p.p.m. is highly questionable when sodium and bicarbonate content of the groundwaters is taken into consideration. Very probably, the high concentration of sodium and/or bicarbonates in all the Punjab and Bahawalpur groundwaters would cause the soil to become completely alkaline much before the salt concentration of the mixed canal-tubewell waters reaches 1,100 p.p.m. This is already being experienced in SCARP-1 area as described in the following subsection.

5) Effect of SCARP-1 Groundwaters on Soils

Fireman and Haque classified the mixed canal-and-tubewell waters from SCARP-1 area into "good", "fair" and, "poor" on the basis of their ESP, and studied their effect on saline-alkaline soils and on normal soils during 1962/63 and 1963/64. According to their classification, "good", "fair", and "poor", waters had total salt content and ESP as shown in Table VIII. Comparing the thirty-four mixed waters of SCARP 1 with the seventy-four tubewell waters of SCARP 1 (Table VI), it will be seen that after mixing with canal water the percentage of safe (good) waters slightly increased and that of marginal

TABLE VIII

CLASSIFICATION OF MIXED CANAL-AND-TUBEWELL WATERS STUDIED FOR THEIR EFFECT ON SOILS IN SCARP-1 AREA

Mixed water	Total salt content in p.p.m.	ESP	Per cent of mixed waters
Good	250-350	4-8	35
Fair	400-600	11-19	26
Poor	600-1000	21-43	38

Source: Calculated from [7, Tables 1 and 2].

(fair) and hazardous (poor) water slightly decreased. However, the improvement in water quality was very small. Percentage of hazardous waters decreased from 39 per cent in the unmixed tubewell waters to 38 per cent in canal-tubewell mixed waters. It is, therefore, unlikely that poor groundwaters all over the Punjab and Bahawalpur could be made fit for irrigation by mixing with canal water. The mixing ratio required to lower the calculated ESP to a safe limit of 10 for the 39 per cent of hazardous groundwaters in SCARP 1 has been calculated as 3.8 parts of canal water to 1 part of tubewell water. It is obvious that canal water on this scale cannot be provided. The total availability of canal water at outlet head is estimated by the Revelle Panel to be 24.3 MAF a year against 49.5 MAF a year of tubewell water. Tubewell installation will, therefore, have to be much more limited.

With regard to their effect on soils, Fireman and Haque found that with the use of mixed canal-and-tubewell waters in saline-alkaline soils, both salinity and alkalinity (exchangeable sodium percentage) decreased significantly in the two-year period. When these waters were used on normal soils, there was a decrease in the salinity and in the exchangeable sodium percentage of the soils irrigated with "good" and "fair" waters. These decreases were attributed to the increased availability of irrigation water. However, there were small but uniform *increases* in the average exchangeable sodium percentage of the normal soils irrigated with the "poor" waters. In these cases, increased water applications did not completely offset the effects of poor quality. They concluded that a mild alkali problem would develop in six to ten years by irrigation of normal soils by these "poor" waters (which are mixed canal-and-tubewell waters). However, Fireman and Haque state that where "poor" waters are used for irrigation, application of gypsum to the soil every few years at the rate of about one-half ton per year would prevent significant soil deterioration.

Results studied by Fireman and Haque are corroborated by the farmers of Sheikhupura district. Some of them complain that their lands irrigated with mixed canal-and-tubewell waters are becoming stiff and that germination of the young seedlings is badly affected[26]. This is the result of two-year irrigation. As more and more of these mixed waters are used over time, much more deterioration of the soil may be expected and the cost of gypsum added to the high cost of pumping may make the use of such waters uneconomic.

From the results of studies by Eaton, Maierhofer, Hausenbuiller, Haque, and Wahab, Maasland, Priest and Malik, Bower and Maasland, and Fireman and Haque, it is evident that tubewell waters cannot be used all over the Punjab and Bahawalpur area even when mixed with canal water for a long-term sustained agricultural development.

C. IMPLICATION OF GROUNDWATER CLASSIFICATION FOR TUBE-WELL INSTALLATION

1) Areas Where Tubewells should be Installed

About 19.5 million acres of culturable land is commanded by canals in the Punjab and Bahawalpur. Tubewells can, for the present, be installed in one-half of this area, that is, about 9.5 million acres which have less than 750 p.p.m. dissolved salts. In addition, there is a gross area of 1.7 million acres (with culturable area of probably 1.5 million acres) in the Sialkot and Gujrat Plain which is not irrigated by canals but is irrigated by open-surface wells and receives high rainfall [22, p. 148]. The salt content of the groundwaters in this area is low, and, therefore, tubewells can be installed in this area. About one million acres of land which receive water from river overflow and has nonsaline groundwaters may also be developed by tubewell installation [22, p. 148]. Thus, in all, tubewells can safely be installed at the present time in about twelve million acres (with the net cultivated area of about ten million acres) against thirty million acres proposed in the *Revelle Report*. Total water requirement for this area will be about thirty-five MAF a year at the rate of 3.5 acre-feet per acre[27]. Out of this about four MAF will be met by recharge from rivers and rains[28]. The balance (thirty-one MAF) must ultimately come from canals—some of this through direct

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[26] This information was supplied to the author by the West Pakistan Department of Agriculture in August 1964.

[27] According to Harza Engineering Company International, the water requirement for crops for different canal systems in acre-feet per acre are: Upper Jhelum, 3.3; Lower Jhelum and Lower Chenab, 3.8; Marala Ravi, 3.0; Raya, 3.4; Upper Chenab, 3.5; Central Bari, 3.8; Lower Bari, 4.2; Upper Dipalpur, 3.7; and Lower Dipalpur, 4.3 [14, p. II-22].

[28] Total rainfall and river seepage for the Punjab and Bahawalpur is estimated by Harza Engineering Company International as 5.7 MAF. As rainfall is heavy in the upper parts of *doabs* more than half of this or about four MAF of recharge from river and rain may be taken for the nonsaline areas [14, p. II-31].

use and remaining through wells capturing the recharge of groundwaters by pumping.

Watersupply for the whole of the Punjab and Bahawalpur is estimated by the Panel as forty-eight MAF a year [44, p. 270]. One-half of this or about twenty-four MAF would be available for nonsaline areas. This should be increased by about seven MAF to provide thirty-one MAF of canal water. This can be accomplished in the next ten years. In the meantime, the farmers can safely mine about seven MAF of water in addition to capturing all the fresh-water recharge. The water budget for nonsaline areas is shown in Table IX. An estimate of cost for

TABLE IX

WATER BUDGET FOR NONSALINE AREAS

	First 10 years	After 10 years
	(million acre-feet)	
Canal water at canal head	24	31
Recharge from rain and river	4	4
Mining of groundwater	7	—
	35	35

increasing the canal capacity by about seven MAF a year should be prepared by the WAPDA or by the West Pakistan Irrigation Department. On the basis of a programme prepared by the West Pakistan Irrigation Department for increasing the capacity of canals during the third-plan period, the cost of increasing the capacity of canals by seven MAF a year is likely to be of the order of about 400 million rupees.

2) Areas Where Tubewells should not be Installed

In the saline areas of the Punjab and Bahawalpur, the Revelle Panel propose to install tubewells to pump 8.9 MAF of groundwater with an average salt content of 6,000 p.p.m., to export 0.5 MAF of this and to mix the remaining with canal water and use the mixed water with a maximum of 2,000 p.p.m. of dissolved salts [44, pp. 274-280]. The average rate of application of water recommended for this area is 4.0 acre-feet per acre. The Panel does not recommend any increase in the supply of canal water for these areas [44, p. 14].

We consider that when the high sodium content of the groundwaters are taken into consideration, it will not be possible to maintain a long-term agriculture with an application of 4.0 acre-feet per acre of water containing 2,000 p.p.m. of dissolved salts. The potential evapotranspiration of the crops for these areas are estimated by the Panel to about 5.0 acre-feet per acre[29]. At another place, the Panel estimate the drainage rate to be 25 per cent to 67 per cent for crops of high-to medium-salt tolerance with waters containing 2,000 p.p.m. of dissolved salts [44, p. 117]. The water requirements, including leaching, for these areas should, therefore, be 6.2 to 8.2 acre-feet per acre instead of 4.0 acre-feet per acre. Obviously, it would not be possible to continue agriculture for a long period with 4 acre-feet per acre of water having 2,000 p.p.m. of dissolved salts particularly when sodium content of these waters is taken into consideration.

We consider that either the total area under cultivation will have to be reduced or application of surface water will have to be increased to these areas.

Harza Engineering Company International consider that total river-water diversions to the Punjab and Bahawalpur canals could be increased to sixty-one MAF a year by 1975 [13, p. 55]. If thirty-one MAF of this goes to the tubewell-canal-irrigated areas, the balance of thirty MAF a year could be delivered to the saline canal-irrigated areas where tubewells are not installed. Adding 1.7 MAF of recharge from rain and rivers would raise the total watersupply to 31.7 MAF a year. Assuming a water requirement of 5 acre-feet per acre and a drainage requirement of 10 per cent, 31.7 MAF a year of canal water would be sufficient to provide irrigation to a net cultivated area of about 5.8 million acres or a gross area of about 7.5 million acres. Total culturable canal-commanded area having more than 750 p.p.m. of dissolved salts is about 9.5 million acres, and the net cultivated area is about 7 million acres. Thus, about two million acres of culturable canal-commanded area or about 1.2 million acres of net cultivated area will have to go out of cultivation. The worst-affected area at the lower ends of the *doabs* where the salinity of groundwater is as high as 20,000 p.p.m. may be allowed to go out of cultivation. This area can be converted into evaporation flats or drainage wastes for dumping of saline effluent out of the drains installed in the remaining area of seven million acres.

3) Other Issues of Consequence

a) Development of Cultivable-Uncultivated Waste Land: In the *Draft Report* the Revelle Panel had proposed that 70,000 acres of uncultivated land in each project area (1.4 million acres in 20 project areas) be brought under crops in the Punjab and Bahawalpur [31, pp. 79-80]. In our previous analysis of *Draft Report*, published in an earlier issue of this *Review*, we had pointed out that as the watersupply was not sufficient for year-round cropping on the areas

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[29] In Appendix A-1 to the *Revelle Report*, the potential evapotranspiration of crops for Multan are estimated to vary between fifty-three inches and seventy inches by various methods. The Panel recommends a figure of 59.6 inches [44. p. 411].

already under cultivation, no new land should be brought under cultivation [9, p. 273]. In the final report, the Panel again recommends that about forty-four thousand acres of land uncultivated at present be brought under crops [44, p. 192].

We reiterate that it is not in Pakistan's interest to bring any new uncultivated area under cultivation, so long as year-round watersupply is not provided to the area already under cultivation. Hansen, Bower and Williams state: "It is a gross error to continue to spread water over more land rather than to intensively irrigate a portion of the available land. Marginal lands and marginal development schemes should be abandoned to provide an adequate watersupply to areas already being irrigated. Intensive irrigation is a prerequisite to permanent arid-region agriculture" [11, p. 10]. In order to keep the movement of salts constantly downward, the intensity of cropping should be raised from 167 per cent proposed by the Panel, when sugarcane is counted in both *kharif* and *rabi*, to about 200 per cent, before any uncultivated area is brought under crops.

b) Depth of Mining: In our previous review of the *Draft Report*, we had suggested that the watertable should be lowered to about 30 to 40 feet below the ground surface instead of the 110 feet proposed in the *Revelle Report* [9, pp. 268-270]. We had suggested this in order to keep pumping costs to the minimum and to keep the proportion of the mined saline water in relation to the fresh-water recharge low in the pumped water.

In the final report, the Panel states that the capital costs as well as the pumping costs would be 57 per cent of the planned total outlay if only fresh recharge water were to be pumped and if the watertable were to be held constant at a 50-foot depth. However, by mining the groundwater to 110 feet, it would be possible to add 4.8 million acres to the total irrigated land. The present value of the net benefits of such a programme was estimated by the Panel as being 8 per cent greater with mining than with pumping of recharge only [44, p. 324]. On this basis, the Panel recommended mining down to a depth of 110 feet.

In calculations of benefits, the Panel has assumed the discount rate to be 4 per cent. It has further assumed that water mined from 50 to 110 feet depth would have the same salinity and the same value for crop production as the fresh-water recharge. These assumptions by the Panel can be questioned on several counts. *First*, the calculations are extremely sensitive to the rate of discount. For example, if a discount rate of 5 per cent was used instead of 4 per cent used by the Panel, the present value of net benefits with mining would be 96 per cent of that obtained with pumping of recharge only instead of 108 per cent estimated with 4 per cent discount rate. With a discount rate of 6 per cent, the net benefits of mining would be only 86 per cent of that with pumping of recharge only. *Secondly,* if the quality of water was taken into consideration, the present value of net benefits with mining would be further reduced. The salt concentrations of shallow groundwaters are generally less because of dilution by canal seepage [10, p. 82]. Therefore, the greater the proportion of mined water in relation to the fresh recharge in the pumped water, the less will be the value of the pumped water for crop production. *Thirdly,* over time the quality of the pumped water will deteriorate and with greater pumping a larger amount of saline water will have to be exported to the Indus which would further decrease the value of crop production in Sind. *Finally,* mining to 110 feet depth will greatly increase the cost of pumping after 30 years, because the recharge will have to be pumped from that depth over an indefinite period. If all those points are taken into consideration, the calculations result in a negative present value of net benefits with mining when compared with pumping of fresh-water recharge only.

The actual economic depth of pumping can be determined by farmers by experience. But regardless of the depth to which the farmers find it economic to pump water, eventually, there must be an equilibrium of water pumped with the amount of recharge to the groundwater. It is, therefore, essential to increase the capacity of the canals to supply more fresh water directly from the canals to the outlets and to increase the fresh-water recharge to the groundwater.

c) *The Salt Balance*: The introduction of salt-balance concept some two decades ago was an important step in the study of salt accumulation in the soils. The salt-balance concerns the ratio between the quantity of dissolved salts in irrigation water delivered to an area and the quantity removed from the area by drainage. If irrigated areas are to be kept in continuous production, it is necessary to maintain a favourable salt balance, in which the outflow of the salt equals or exceeds its inflow.

On an average, during the five years ending 1956/57, about forty-four MAF of water were diverted into the Punjab and Bahawalpur canals [44, p. 69]. The average salt content of the canal waters is about 250 p.p.m. The total salt added to the Punjab and Bahawalpur lands and groundwater from canal water is, therefore, some thirteen million tons annually. The Revelle plan tubewell-waters will add about ninety-eight million tons of salt to the soil every year (Table X). Most of this will be from the salt originally present in the soil and in the groundwater or that received from irrigation water during the last fifty to sixty years.

TABLE X

SALT WHICH WOULD BE ADDED TO THE PUNJAB AND BAHAWALPUR LANDS UNDER THE REVELLE PLAN

Area	Water	Salt content	Total weight of salt
	(MAF)	*(p.p.m.)*	*(million tons)*
Whole area	44.0 (canal)	250[a]	13
Nonsaline	40.6 (tubewell)	700[b]	34
Saline	8.9 (tubewell)	6,000[c]	64
		Total	111

Sources : *a*) [44, p. 275].
b) [44, p. 272].
c) [44, p . 272].

The total addition to the salt content of the soil and groundwater will be 111 million tons a year. Assuming that 40 per cent of the canal water and 15 per cent of the tubewell water seeps down to the watertable about twenty million tons of salt will go to the groundwater and about ninety-one million tons will remain in the soil. Against this, the Revelle Panel proposes the removal of one MAF of highly saline water during the first ten or twenty years and 3.9 MAF a year thereafter[30]. This water is expected to have a salt content of 4,000 p.p.m. [42, p. 282]. Thus, only about five million tons of salt will be removed annually from the Punjab and Bahawalpur soils during the first ten or twenty years and about nineteen million tons a year thereafter[31]. Thus, it is clear that removal of salt is only a fraction of its accumulation in the soil. The Punjab and Bahawalpur lands cannot be kept in continuous production under this system.

For the Khairpur project area (0.3 million acres) in Sind, which is proposed to be reclaimed through drainage tubewells, Hunting Technical Services state that 356 thousand tons of salt arrive in the canal and 1,377 thousand tons leave in the Rohri canal annually. There is, thus, a favourable salt balance for the Khairpur area. But the salt content of the Rohri Canal which serves by far the best area in Sind will increase. On this subject, Hunting Technical Services state that :

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30 At another place, the *Revelle Report* gives a figure of 10 per cent of 59 MAF or 5 MAF of saline water to be exported [44, p. 305].

31 Or twenty-four million tons if five MAF of saline water is exported.

" We do not propose to allow the salinity of the Rohri canal water when mixed into tubewell water to exceed 600 p.p.m. and to keep within this limit, we would temporarily reduce the drainage facilities for the Khairpur Feeder East system if this should ever be necessary" [18, p. 23]. Thus, there is no gain in removing the salt from Khairpur and adding it to Rohri canal. Total salt content of the Sind and Khairpur as a whole would increase and not decrease.

D. DRAINAGE OF SALINE LANDS

If tubewells are not installed in the saline areas, how should these areas be reclaimed from excessive salinity and waterlogging? For these areas, we recommend the installation of a system of deep open main drains combined with open and/or tile field-drains[32]. The open drains in varying degrees are, as we have seen, a common feature of almost all irrigation projects in the United States, Egypt and the Soviet Union [23, pp. 1-30; 32, pp. 51-72; 35, pp. 1-53]. Open drains are usually supplemented by tile drains which collect drainage waters from the fields and discharge them into the main open drains. In many irrigation projects in the Soviet Union and in most of Egypt, field drains are also open and not tiled or covered [32, p. 10; 35, p. 36].

1) Drains Versus Tubewells in Saline Groundwater Areas

Although tubewells are extensively used for *irrigation* purposes in the United States, they are specifically used for *drainage* only in a few irrigation districts like the Salt River Valley Irrigation District of Arizona and in the San Joaquin Valley of California. In both these places, the success of tubewell programme in reclaiming waterlogged and saline land is attributed to two major factors, namely, ample layers of water bearing gravel in the subsoil strata and the very low electric power costs. The tubewells provide valuable supplementary water and the drainage value of these wells is now incidental to their irrigation value.

In other places like the Imperial Valley of California and the Rio Grande Valley of Texas, tubewells were installed for drainage purposes but had to be abandoned [35, p.87]. Except for experimental purposes, no tubewells are installed for drainage purposes either in the Soviet Union or in Egypt [32, p. 18 and

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32 A drain is a conduit or channel either natural or artificial for carrying surplus surface or groundwater. The drains are of various kinds.

Tile drain is a pipe of burnt clay or concrete, in short lengths, usually laid with open joints to collect and remove drainage water.

Collector drain is the smallest category of open drain. Its direct function is to maintain the watertable at a desired level and to provide for movement of leaching water.

Subdrain is one into which collector drains flow. As proposed for the Lower Indus Plain, the subdrains are aligned between canal distributories and minors.

Branch drain collects water from two or more branch drains.

Main drain collects water from two or more subdrains.

35, p. 44]. There is no reason why these should be installed for pumping of saline water in West Pakistan where electric power is much more expensive than in the United States, the Soviet Union and Egypt. There is no reason why deep open main drains combined with open and/or tile drains should not be constructed in West Pakistan where labour is much cheaper and most of the drains can be dug with hand labour. Maierhofer considers that: "Other pressures in the form of indefensible promises of benefits to be derived from the purchase and installation of certain well screens, casing and pumping equipment have detracted from progress" [23, p. 277].

The *Revelle Report* does not recommend a system of open and/or tile drains in West Pakistan. They give two reasons for this:

i) The West Pakistan irrigation plain is remarkably level and on account of the mild slope it is difficult to utilize the surface drainage extensively for the return of drainage flow to the rivers [44, p. 259].

ii) For the Punjab, the Revelle Panel's calculations show that the surface and subsurface drainage is not only more expensive than tubewells for eliminating waterlogging and salinity, but they do not provide the outstanding advantage of the latter, *i.e.*, increase and regulation of the irrigation supply [44, p. 269].

Regarding mild slope and movement of drainage waters on level plains, Maierhofer has pointed out that if water can be moved by gravity in irrigation canals, it can also be moved by gravity in the drains in the same area [23, p. 15]. Drainage is certainly difficult in such flat areas, but it can be accomplished economically if some power is used for pumping to supplement existing gradients.

With regard to cost, the Panel might have based its judgement on tile drains being more expensive than tubewells on the basis of information contained in Feasibility Report on SCARP 2 (Chaj *Doab*) prepared by Tipton and Kalmbach Inc., Consultants to WAPDA [37, pp. A-1 to A-6]. In this report Tipton and Kalmbach assume that:

i) Both methods (tubewells and tile drains) require an electrification network throughout the area to be reclaimed with power service supplied to a point within each 600 to 700 acres of land. For 2.3 million acres of land in SCARP 2, 3,550 sump pumps would be required with tile drains. Alternatively, 3,311 tubewells would be required for the same area.

ii) Both methods require, in addition to the facilities for drainage of sub-soil, adequate surface drainage works to take care of storm runoff and overland flooding.

iii) The drains would be six feet deep and would vary in spacing from 250 feet in fine-textured soils upto 650 feet in coarse-textured sands.

iv) Average life of both tubewells and the tile drains would be forty years.

v) Level of crop production under a tile-drainage system could be expected to be about one-and-one-half times the present level. With tubewells for irrigation and drainage, crop production could be expected to be about double the present level.

We consider that most of the above assumptions by Tipton and Kalmbach are incorrect:

i) While a tubewell-drainage system does need an electrification network for pumping of water, a tile-drainage system does not need one. If water can move in the Lower Jhelum Canal by gravity throughout the SCARP-2 area, it can certainly move in the drains by gravity in the same area [23, p. 15]. The idea of having 3,550 sump pumps with tile drains is based on the wrong idea of the efficiency of drains. The tile drains should discharge into collector drains which should discharge into deep main open drains and not into pumpage sumps. Lands having equally flat gradients are being drained in the Lower Rio Grande Valley of Texas and other irrigated areas of south western United States with only minor pumping required in some cases [23, p. 15].

ii) A system of surface drains is needed to remove the pumped water from tubewells in saline areas. It is not needed to take care of storm runoff. Rain water being free from salts is very valuable. It should percolate down into the soil and move through the tile drains into main deep drains.

iii) Most of the areas in the Chaj *Doab* are underlaid at shallow depth by medium to coarse sands. For such areas, the average spacing for tile drains laid at eight to ten feet depth is estimated as 800 to 1,500 feet instead of 200 to 650 feet assumed by Tipton and Kalmbach [23, p. 19],

iv) The average life of tubewells in saline groundwater areas will be much less than forty years. Harza Engineering Company International expect the life of tubewells to be only twenty years [13, p. 49]. On the other hand, tile drains made of clay are chemically inert and have an almost indefinite life [32, p. 25]. Some of the clay tiles laid over one hundred years ago in the United States are still working successfully [21, p. 3].

v) With tubewells pumping saline water, the salt content of the mixed canal-and-tubewell water is expected to be 1,100 p.p.m. of dissolved salts in the saline part of the SCARP-2 area [37, p. 487]. Such water can be used if 11 to 67 per cent additional water over the consumptive use of crops is provided [44, p.117]. Water application in these cases should, therefore, be about four to six acre-feet per acre instead of two acre-feet per acre proposed for SCARP-2 area (4.5 MAF on 2.3 million acres). With this depth of water and with high sodium and bicarbonate content of the pumped water, it will not be possible to maintain agricultural production at the existing level. There is no possibility of doubling agricultural production in the saline groundwater areas included in SCARP 2 over a long-term period. On the other hand, tile drains will progressively desalinize the soil and demineralize the groundwater through continuous removal of saline effluent out of the area if additional canal water is provided to leach out the salts. Under such conditions production can increase much more than the 50 per cent assumed in the Feasibility Report.

Whatever material was available and considered by the Panel, the material supplied by Tipton and Kalmbach to prove that tile drains were more expensive than tubewells in the Punjab, was based on incorrect assumptions in most cases.

The Revelle Panel was aware of the surplus farm labour available in West Pakistan which could do the digging of open field and collector drains at near zero cost to the economy. For when they calculate the cost of cultivation of an additional 380 thousand acres to be brought under crops by tubewell water in each project area (9.5 million acres in 25 project areas) the cost of labour is regarded as zero because, according to the Revelle Panel, "there is considerable surplus of farm labour which can be applied to land without sacrificing valuable output elsewhere" [44, p. 193]. An application of the same principle to the labour required for digging of drains, would have shown that open drains are not only more economical than tubewells, but that their cost is only a small fraction of the cost of tubewells installed by the government through foreign contractors using imported materials. Dr. C. A. Bower, Director of the United States Salinity Laboratory, Riverside, California, Dr. V. E. Hansen, Director, Engineering Experiment Station, Logan, Utah, and Dr. F. J. Williams of Rice Experiment Station, Stuttgart, Arkansas, visited the Lower Indus Basin of West Pakistan in July and August 1962. They recommend a phased construction of drainage system. They state "a drainage system may initially consist of only the major lines, with branches to drain only surface accumulation of water. The farm drainage might under some circumstances be justifiably deferred until the needs become more acute" [11, p. 19]. They further state that "providing an open drainage system with gates so that water level in the channels can be controlled has several benefits for rice area of Sind. With small land slopes encountered in the Indus Basin the elevation of the water table can be controlled to fit cropping needs.... The drainage system should be designed to permit maximum reuse of drainage flows and adequate mixing of saline groundwater with canal water. By mixing, the total water supply will be increased, drainage conveyance costs will be reduced, the economics of lowering saline water tables will be improved and storage capacity for underground recharge will be increased" [11, pp. 16-17].

A system of providing gates in the drains as recommended by Hansen, Bower and Williams, is already being used in the Soviet Union where the water-table is raised by checks in the drains during periods of water shortage to overcome drought conditions.

2) Cost of Construction of Open Drains in Pakistan

With regard to the cost, the Panel does not give their calculations to show how the open drains were found to be more expensive than tubewells in the Punjab. Open field-drains and open collector-drains have been provided in a small area of about 3,600 acres at Chakanwali on the Lower Chenab Canal in the Punjab. This area had been abandoned due to waterlogging and salinity but has been successfully reclaimed by open field-drains dug about 4 feet deep and 220 feet apart. According to the Director, Land Reclamation, West Pakistan, the cost of construction of such drains under the *present* rates is seventeen rupees per acre for tiled drains and twenty rupees per acre for collector drains or a total of thirty-seven rupees per acre [26, p. 190].

Hunting Technical Services estimated the cost of open drains in Khairpur and in the perennial areas of Ghulam Mohammad Barrage (GMB) as 220 and 300 rupees per acre respectively.

For Khairpur, the cost was estimated as follows [15, p. 50][33]:

Collector drains		rupees	113 per acre
Main drains		rupees	108 per acre
	Total	rupees	221 per acre

[33] In January 1961, Hunting Technical Services proposed drains for Khairpur area estimated to cost 221 rupees per acre [15, p. 50].

In June 1961, Hunting Technical Services stated "our conclusion is that the area east of Rohri Canal should be drained by open drains and that area west of Rohri should be drained by Tubewells". It was confirmed that area east of Rohri had very saline groundwater. Capital

(Contd. on page 392)

For Gaja perennial area of Ghulam Mohammad Command, the cost was estimated as follows [16, p. 45]:

Collector drains	rupees	214	per acre
Main drains	rupees	87	per acre
Total	rupees	301	per acre

The cost of collector drains was high in Gaja command of the GMB because the soil is heavy and collector drains were to be located at 900 to 1,100 feet apart compared to 1,300 feet for Khairpur area. On the other hand, the cost of main drains was lower in the Gaja command because of the shorter distance to which the water was to be moved.

The cost of the major items of the collector drains dug 1,100 feet apart in the Gaja command of GMB is estimated at 142 rupees per acre (Table XI).

TABLE XI

COST PER ACRE OF COLLECTOR DRAINS IN THE GAJA COMMAND OF GHULAM MOHAMMAD BARRAGE

Item	Collector drains	Subcollector drains	Total cost per acre of gross area
	(....................	*rupees per acre*	..............)
Earthwork	63	35	98
Structures	2	2	4
Land	17	10	27
Miscellaneous	8	5	13
Total	90	52	142

Source : [16, p. 42, Table 26].

Where the drains were to be laid at 900 feet apart, the total cost was estimated at 169 rupees per acre. The average for the two came to 156 rupees per acre. To this cost was added contingencies at 5 per cent, engineering cost at 15 per cent and interest during construction at 4 per cent. The total cost then came to 196 rupees per acre of the gross area. This was equal to 214 rupees per acre for the culturable commanded area.

(*Contd. from page 391*)

cost of tubewells was estimated as 137 to 163 rupees per acre, whereas that of open drainage system was estimated at 214 rupees per acre [17, p. 7].

In 1962, Hunting Technical Services presented recommendations for a tubewell project for the whole area of high watertable in Khairpur. This was to include areas which had been confirmed to have very saline groundwater. The capital cost of the tubewell project was estimated at 481 rupees per acre. In this report, the cost of drains was raised to 959 rupees per acre [18, p. 9].

For the main drains, the distribution of cost in rupees per acre was estimated as under [16, pp. 48-50]:

	(rupees per acre)
Land	4
Earthwork	47
Structures	6
Pumps	8
Miscellaneous	4
Total	69

To this was added contingencies, engineering cost and interest and the total cost came to eighty-seven rupees per acre. It will be seen that major component of cost is earthwork, equal to about one hundred rupees per acre for collector drains and fifty rupees per acre for main drains. This is equal to about sixty man-days per acre. As is wellknown, underemployment is widespread in the rural areas of Pakistan. According to the Planning-Commission estimates, unemployment and underemployment during the third-plan period will amount to nearly eight million manyears per year [30, p. 25]. Digging of drains for each five million acres would provide employment to one million men for a year. This can be arranged through Rural Works Programme for the main and branch drains while all field and collector drains can be completed by the farmers in their spare time in a few years without any real cost to the economy.

The next major item is land (about thirty rupees per acre). Total area under the present canal command is much more than the available water supply can support. Hansen, Bower and Williams recommend that marginal lands should be abandoned to provide an adequate watersupply to the areas irrigated [11, p. 10]. Even if drains pass through some good lands, it will not result in decrease in production, but the application of adequate water to the remaining area will increase total production. Land without water in West Pakistan is useless. The cost of land can, therefore, be neglected from the cost of drains.

The only real cost is the cost of structures which is about four rupees per acre for collector drains and about fourteen rupees per acre for main drains. In addition, cost of engineering services would come to about thirty rupees per acre. The real cost of the drains is, thus, about fifty rupees per acre.

3) Cost of Construction of Tile Drains

Dr. Eaton estimated the cost of tile drains for Pakistan on the basis of 400-foot spacing and 1950 costs in California as 50 dollars per acre or 250 rupees. This is based on the assumption that the work will be done by imported tile-laying machines [5, p. 15].

Maierhofer gives the cost of tile field-drains *plus* deep open main drains in the United States as 50 to 200 dollars, or 250 to 1,000 rupees per acre, the difference being primarily dependent upon land gradients and soil profiles capacity for vertical and lateral water conductivity. For Pakistan, Maierhofer considers that it may be possible to accomplish the task at much less cost, as hand labour would be appreciably cheaper for doing the work than would power equipment [23, pp. 17-20]. He cites the example of another (unnamed) country where wages were twenty cents per hour for unskilled workers and fifty cents per hour for skilled tile-layers. At these wages, the costs were about one-third those of comparable work by power equipment. In Pakistan rural areas, wages for unskilled workers are only five cents an hour (two ruppees per day) and those for skilled workers about fifteen cents an hour (six rupees per day). It would, therefore, be possible to lay tile drains and dig open collector and main drains with hand labour at much less than 50 to 200 dollars per acre if the government were prepared to forget the hopelessly unrealistic task of accomplishing all drainage works with imported machinery.

4) Disposal of Drainage Waste

Under ideal conditions, the saline drainage-waste should discharge into the sea or natural depressions. This can be done for the lower Indus Plains. But for the Punjab and Bahawalpur disposal of saline waste into the sea would be too costly in view of the long distances involved.

Drainage water can be disposed of into drainage wastes or evaporation flats in the lower reaches of the *doabs*. Evaporation from free water surface in these areas is of the order of eighty to ninety inches a year [4, p. D-3 to D-8]. As much as seven MAF a year of drainage effluent could, therefore, be evaporated from one million acres of evaporation flats.

Total area for which drains are to be provided in the Punjab and Bahawalpur is about seven million acres with a net cultivated area of about 5.8 million acres. Total watersupply for this area is estimated as thirty MAF a year. If 10 per cent of this is removed in the drains, the total drainage effluent will be about three MAF a year. This can be evaporated from about half a million acres of waste land. This land can be selected out of the noncultivated area or from the abandoned areas in the lower reaches of the *doabs* where salt concentration of the groundwater is the highest.

Contrary to proposal of the Revelle Panel, this will not increase the salinity of the irrigation water in any canal in the Punjab and Bahawalpur and will not cause any increase in the salinity of the Indus water entering Sind.

With provision of drains, there will be rapid and progressive improvement in the salinity of the soils and groundwater in these areas. Eventually, we should reach a stage when the groundwater will be far less saline and could be reused for irrigation. In the perennial area of the Ghulam Mohammad Command, groundwater salinities are higher than the salinities of the saline groundwater areas of the Punjab and Bahawalpur. For Ghulam Mohammad Command, Hunting Technical Services proposed field drains spaced 900 to 1,500 feet apart for a water level six feet below ground surface. Irrigation supply for this area was estimated at 4.4 acre-feet per acre at the canal head. With this water and surface drains six feet deep, they expected the groundwater to have less than 2,500 p.p.m. of dissolved salts. Under our proposals, the tile drains, laid at eight to ten feet deep, in the saline areas of the Punjab and Bahawalpur with canal watersupply of 5.5 acre-feet per acre, should remove the salt from the soil as well as from the groundwater up to about fifteen to twenty feet below ground-surface when the surface water percolates down and enters the tile lines from below along with the saline groundwaters. This has been accomplished in ten to fifteen years in the Soviet Union [32, pp. 62-64].

5) Increase in Crop Production on Drained Land

The increase in agricultural production on land drained by open and/or tile drains would be much higher than that obtained by the installation of tube-wells and the use of saline water for irrigation. As an example, in the Uzbekistan Republic of the Soviet Union, the yield of cotton has increased from 16.3 maunds per acre in 1940 to 31.7 maunds per acre in 1959 due to provision of open main drains combined with other improved practices [32, p. 101]. For those areas where open drains have been supplemented with tile field-drains, the yield of cotton has increased to forty to fifty maunds per acre or even more [32, p.100]. Similarly, the Imperial Valley of California had never been prosperous before the installation of tile drains. Families repeatedly lost all of their savings and moved away [5, p. 28]. In December 1945, the Operation Division of the Soil Conservation Service began, in cooperation with the district authorities, preparing drainage plans for the farmers[35, p. 24]. Several thousand miles of tile drains were installed in the Imperial Valley lands in the next few years. The results were so striking and practical that immediately thereafter the Federal Land Bank began to make loans on tile-drained land whereas no loans were granted previously [5, p. 28]. On the other hand, in the Khairpur project area in Sind where tubewells are proposed to be used for reclamation of saline and waterlogged lands, Hunting Technical Services State : "We do not think that drainage by itself will result in very large increases in crop yields. Our basic assumption in calculating the benefits of drainage are that the immediate impact of drainage, with no change in methods of farming or increases in other inputs, should result in an approximate 25-per-cent improvement in crop yields and that this drainage accompanied by a successful extension and research service and the progressive removal of social and economic barriers to increased production will raise crop yields to 100 per cent of their present value." [18, p. 10]. As we have previously pointed out, any increase in production by pumping of saline water in one area is likely to be offset by a decrease in production in downstream areas where the saline pumped waters are used after mixing with canal water. In our judgement, the best method for saline groundwater areas would be drains and not tubewells.

6) Water Economy on Drained Land

One great advantage of tile drainage is that it materially reduces the water requirements of crops to be met from irrigation. This is because roots of most crops grow in the direction of increasing soil moisture. The greater the depth of drained soil, the greater will be the root penetration, feeding area, available plant food supply and drought resistance of crop [39, p. 9].

Tipton and Kalmbach regard this as a disadvantage rather than an advantage. According to W. W. Donan, a drainage engineer engaged by Tipton and Kalmbach, tile drains and open drains can lower the watertable to four feet below ground surface [4, p. D-8]. At this depth, there is an evaporation opportunity[34] of about 0.12 inches per day or 43 inches per year. On the premise that about half of this evaporation opportunity might actually occur, there could be a loss of about eighteen inches of water from a tile-drained land. On the other hand, by pulling the watertable to below ten feet with tubewells, the loss of water could be decreased to about three to four inches a year, thus saving a considerable volume of water.

We choose to put the same proposition in the opposite way, If tiles are laid at eight to ten feet depth, the watertable will remain at about six to nine feet depth. When crops are grown on such tile-drained lands throughout the year, the underground water could supply about twelve inches or more of water requirements of crops when the groundwater has been demineralized in a few years. Consequently, less canal water would be required. This is what is being done in the Soviet Union where the tile drains are laid about six-and-half to eight feet deep. The watertable is kept at five to six-and-half feet below surface. Under these conditions, cotton plant obtain 30 to 50 per cent of their water requirement from the groundwater reservoir and only 50 to 70 per cent of the requirements have to be applied in irrigation water.

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[34] Evaporation opportunity refers to the amount of water that could evaporate from a soil surface under a given set of climatic conditions and with watertable held at a given depth below the soil surface.

This view is supported by Hansen, Bower and Williams. They state as follows: "Care should be exercised in lowering the watertable much below the maximum root zone of the crop. A considerable portion of the consumptive use requirements will be met from groundwater under favourable conditions. Lowering the watertable below the reach of mature roots will increase proportionately the amount of water that must be applied by irrigation from limited surface water supplies. Thus, a water table supplying water to the lower portions of the root zone will be very beneficial from the view point of water supply, but will have disadvantages due to increased evaporation from the soil and increased accumulation of salts. A watertable between the two extremes is the most desirable depth. However in applying this concept, care must be exercised to insure that adequate salinity control results. If good control of the watertable cannot be assured a deeper table may be advisable." [11, pp. 13-14]. They further add: "The depth from which roots can extract moisture from the soil should be determined. With the high rates of consumptive use, depths would be expected to exceed those encountered in more temperate climates. Thus, crops requiring two months to mature may have roots penetrating to three feet, crops requiring four months to mature may have roots six feet deep, and a six-month crop may have roots extending to ten feet." [11, p. 23].

The above estimates of Hansen, Bower and Williams regarding the depth from which roots may extract water are confirmed by preliminary experiments carried out by the Irrigation Research Institute at Lahore. The Institute has carried out experiments on the evapotranspiration of crops with watertable held at different depths. It was found that a large part of the water requirements of crops could be met from the groundwater storage when watertable was held at five to nine feet depth. The results of their work are summarized in Table XII. In the case of cotton more than 40 per cent of the evapotranspiration requirement was met by the groundwater at nine feet depth. In the case of wheat, 45 to 80 per cent of the total requirement was met from groundwater maintained at five to six feet below ground surface. In the case of barley, gram and lentil, 70 to 95 per cent of the total water requirement were met from groundwater and only a small fraction of water requirement had to be supplied as surface irrigation.

The work on evapotranspiration of crops at the Irrigation Research Institute, Lahore has been in progress since one or two years only. The experiments were carried out in small lysimeters or hume pipes. It is not definitely possible to conclude that under field conditions as much as 40 to 95 per cent of water requirement of various crops will be met from the groundwater when water is held at five to nine feet depth. There is no doubt, however, that, as predicted

TABLE XII

EVAPOTRANSPIRATION OF DIFFERENT CROPS AND THE REQUIREMENT MET FROM SURFACE IRRIGATION, RAINFALL AND GROUNDWATER

Crop	Watertable below ground surface	Evapotrans-piration	MET FROM			Percentage of evapotranspiration met from groundwater
			Surface irrigation	Rainfall	Ground water	
	(feet)	*(inches)*	(..............*inches*.. ....)			
Cotton	9.0	40.3	16.0	6.5	16.9	44
Wheat 1962/63	5.7	19.9	3.1	1.0	15.8	79
Wheat 1963/64	5.0	26.3a	15.8	1.3	11.6	44
	6.0	22.6b	15.8	1.3	10.0	44
Barley	4.7	17.9	4.1	1.0	12.8	71
Gram	5.0	18.8	—	1.0	17.8	95
Lentil	6.0	13.3	3.1	1.0	9.3	70

Notes:
a) Of this 2.4 inches infiltrated to the watertable.
b) Of this 2.1 inches infiltrated to the watertable.

Source: [27, pp. 13—22].

by Dr. Bower and his associates, a considerable part of the water requirements of crops can be met from the groundwater when a system of deep open main drains combined with open and/or tile field-drains is installed. In the Soviet Union, they are already meeting 30 to 50 per cent or more of the water requirement of cotton and other crops from the groundwater. We can probably do the same in the saline groundwater areas when the salts have been removed from the soil and upper part of the groundwater demineralized by installation of a system of drains.

E. ORGANIZATION FOR LAND AND WATER DEVELOPMENT

The Revelle Panel proposes that the major part of irrigated area of West Pakistan be divided into twenty-five to thirty project areas of about one million acres each. It further proposes that each project area be put under the charge of a project director with competent and adequate staff for operation of tubewells and modernizing the agriculture of his area. The Panel proposes that new project areas should be brought into the programme at the rate of about one every year and the entire programme should be completed in twenty-five to thirty years.

We consider that it is not necessary to open project areas and provide a large staff for operation of tubewells in such areas. As we have pointed out previously, it is not desirable to install any tubewells in the saline groundwater areas in the Indus Plain. These areas should be developed by providing deep open main drains combined with open and/or tile field-drains and increased canal watersupply. Tubewells should be installed only in good groundwater areas.

According to a survey carried out by the Pakistan Institute of Development Economics, private tubewells are being installed in these areas by the farmers at a far less cost than the government tubewells. Farmers are saving and investing considerable funds and rural capital formation, so badly needed for economic development, is taking place. Further, the farmers are getting much larger increases in agricultural production where they have installed their own tubewells than in the areas where the government has installed the tubewells. For details readers are referred to the last issue of this *Review* in which results of this survey were published [8, pp. 233-243]. We, therefore, recommend that the West Pakistan Government should concentrate on providing electric-transmission facilities to the good groundwater areas, extend long-term credit, and provide other ancillary facilities required by the farmers for the installation of tubewells. If these facilities are provided, the farmers may complete the installation of tubewells in all good groundwater areas within a period of five to ten years.

Drainage for the development of saline groundwater areas through deep open main drains and open and/or tile field-drains calls for government attention. The main and branch drains will have to be laid first. A masterplan for these should be prepared by the government and work executed under the Rural Works Programme. Field drains will have to be dug by the farmers themselves, but technical assistance must be provided by the government. Layout of field drains should be marked by the government and farmers should be asked to dig the part of the drain passing through their holdings. As one field drain may run over the holding of many cultivators, the government will have to assume power to ask any reluctant land holder to undertake the digging of the drain marked through his holding. When the farmers see the increase in agricultural production brought about by drainage they will surely take up the job without much difficulty. As soon as laying of open field-drains is started, part of these should be covered tile drains, again the government cooperating with and helping the farmers in this job.

IV : CONCLUDING REMARKS

In sum, the information presented in this paper, on the chemistry of groundwaters and relative benefits and costs of the tubewell programme presented in the *Revelle Report*, and a feasible alternative programme of deep open main drains combined with tile field drains, raises serious questions about the major recommendations of the Revelle Panel. Information available on the chemistry of the groundwaters indicates that active implementation of the programme recommended by the Revelle Panel and now under execution in SCARP areas should be postponed. Pending further investigations, tubewell installation should be limited to the best groundwater areas. If the farmers are encouraged to play an active role in the installation of private tubewells, the programme would both cost drastically less and achieve a great deal more. A large expansion of the electrification programme to cover all nonsaline groundwaters should be undertaken to expedite the installation of private tubewells. On the other hand, in saline groundwater areas, installation of a system of drains with adequate canal watersupplies would bring far greater increases in production at far less real cost to the country than the installation of tubewells for pumping and use or export of saline water. A programme for diversion of additional river water and increasing the capacity of canals, both in the saline and nonsaline groundwater areas should be initiated for this purpose.

It is to be hoped that the Panel's recommendation will be reconsidered and modified along the lines indicated in this paper before these are implemented.

REFERENCES

[1] Agricultural Development Bank of Pakistan. *Annual Report and Statement of Accounts for the Year ending June 1962.* (Karachi: Agricultural Development Bank of Pakistan, 1963).

[2] Beanchamp, Keith H. "Tile Drainage—Its Installation and Upkeep", *Water, The Yearbook of Agriculture, 1955.* (Washington, D.C.: US Department of Agriculture, 1955).

[3] Bower, C. A. and Maasland, M. "Sodium Hazard of Punjab Groundwaters", *Symposium on Waterlogging and Salinity in West Pakistan.* (Lahore: West Pakistan Engineering Congress, October 1963).

[4] Donnan, W. W. "Evaporation of Ground Water," *Feasibility Report on Salinity Control and Reclamation Project Number Two, Chaj Doab.* (Denver: Tipton and Kalmbach, 1960).

[5] Eaton, Frank M. *Report to the Government of Pakistan on Certain Aspect of Salinity in Irrigated Soils.* (Rome: Food and Agriculture Organization, September 1953).

[6] Edminster, T. W. and Reave, Ronald C. "Drainage Problems and Methods", *Soil, The Yearbook of Agriculture, 1957.* (Washington, D.C.: US Department of Agriculture, 1957).

[7] Fireman, Milton and Haque, M.A. "Progress Report on Effect of Tubewell Waters on Soils in SCARP 1", Note supplied to the author by M. Maasland of Harza Engineering Company International in August 1964.

[8] Ghulam Mohammad. "Some Strategic Problems in Agricultural Development in Pakistan", *Pakistan Development Review,* Vol. IV, No. 2, Summer 1964.

[9] ———————— and Beringer, Christoph. "Waterlogging and Salinity in West Pakistan: An Analysis of the Revelle Report", *Pakistan Development Review,* Vol. III, No. 2, Summer 1963.

[10] Greenman, D. W., Swarzenski, W.V. and Bennet, G. D. *The Groundwater Hydrology of the Punjab, West Pakistan, Bulletin No. 6 of the Soils and Investigation Division of WAPDA.* (Lahore: West Pakistan Water and Power Development Authority, 1963).

[11] Hansen, V. E., Bower, C.A. and Williams, G. J. *Salinity Control and Reclamation Programme in the Lower Indus Basin.* (Lahore: Harza Engineering Company International, 1963).

[12] Harza Engineering Company International. *Programme for Water and Power Development in West Pakistan, 1963—1975. Supporting Studies. An Appraisal of Resources and Potential Development.* (Lahore: Harza Engineering Company International, September 1963).

[13] ————————. *Programme For Water and Power Development in West Pakistan through 1975.* (Lahore: West Pakistan Water and Power Development Authority, January 1964).

[14] Hausenbuiller, R. L., Haque M.A. and Wahab, Abdul. "Some Effects of Irrigation Waters of Differing Quality on Soil Properties", *Soil Science,* Vol. 90, pp. 357-364, quoted by C. A. Bower and M. Maasland [3].

[15] Hunting Technical Services Ltd. *Sukkar-Guddu-Ghulam Mohammad Drainage and Salinity Control Project, Report No. 1, Khairpur Command.* (London: Hunting Technical Services Ltd., January 1961).

[16] ————————. *Report No. 2, Gaja Perennial Area.* (London: Hunting Technical Services Ltd., May 1961).

[17] ————————. *Report No. 3, Khairpur Command Supplementary Report.* (London: Hunting Technical Services Ltd., July 1961).

[18] ————————. *Report No. 3, Khairpur Project Planning Report.* (London: Hunting Technical Services Ltd., 1962).

[19] ————————. *Report No. 4, Ghulam Mohammad Barrage Command.* (London: Hunting Technical Services Ltd., July 1961)

[20] ——————————. *Report No. 5, Sukkur-Guddu-Right-Bank Command.* (London: Hunting Technical Services Ltd., October 1961).

[21] King, James A. and Lynes, W. S. *Tile Drainage.* (Mason City: Mason City Brick and Tile Co., 1946).

[22] Maasland, M., Priest, C. E. and Malik, M. S. "Development of Groundwater in the Indus Plain", *Symposium on Waterlogging and Salinity in West Pakistan.* (Lahore: West Pakistan Engineering Congress, October 1963).

[23] Maierhofer, C. R. *Reconnaissance Report: Drainage, Waterlogging and Salinity Problems of West Pakistan.* (Denver: US Bureau of Reclamation, October 1952).

[24] Majid Hasan Khan. *Wells and Tubewells.* (Lahore: Supdt. Government Printing West Pakistan, 1959).

[25] ——————————. *Appraisal of Work Done by the Agricultural Machinery Organization, Northern Zone.* (Lahore: Supdt. Government Printing West Pakistan, 1960).

[26] Husain, Mohammad and Nishat, H. A. "Review of Reclamation Activities and Methods and Suggested Measures for Waterlogging and Salinity Control", *Symposium on Waterlogging and Salinity in West Pakistan.* (Lahore: West Pakistan Engineering Congress, October 1963).

[27] Nazir Ahmad, Akram, Mohammad and Ahmad, Shabir. *A Study of Evapotranspiration of Crops under Varying Conditions of Watertable and Soil.* (Lahore: Irrigation Research Institute, 1964).

[28] —————————— and Sheikh, Mohammad Sadiq. *A Statement of Coir String Strainer Tubewells Installed by Farmers in the Ex-Punjab and Bahawalpur Area.* (Lahore: Irrigation Research Institute, 1963).

[29] —————————— and Qureshy, M.A. *A Study of the Performance of Different Types of Strainers Installed in an Area Between Upper Chenab Canal and Sheikhupura Commonly known as Shadman and Chichoki Mallian Reclamation Schemes.* (Lahore: Irrigation Research Institute, 1964).

[30] Pakistan, Planning Commission. *Outline of the Third Five Year Plan (1965—70).* (Karachi: Planning Commission, August 1964).

[31] President Kennedy's Science Advisory Committee. White House Interior Panel, *Draft Report on Waterlogging and Salinity in West Pakistan.* (Washington, D.C.: Supdt. Doc., September 1962).

[32] Qureshi, M. S. *Control of Salinity and Ground Waters in the Agricultural Lands of U.S.S. R. A Report of the Delegation of Pakistan on Waterlogging and Salinity Control Problems in U.S.S.R., together with an Account of Practices in Cotton Cultivation, Collective and State Farms, Sheep Breeding, Afforestation and Associated Farms, Sheep Breeding, Afforestation and Associated Activity.* (Karachi: Ministry of Industries and Natural Resources, 1963).

[33] Richards, L. A. (ed), *Diagnosis and Improvement of Saline and Alkali Soils.* (*Agriculture Handbook No. 60*). (Washington, D.C.: US Department of Agriculture, 1954).

[34] Taylor, Mackenzie, Malhotra, J. K. and Mehta, M. L. *An Investigation of the Rise of Watertable in the Upper Chenab Canal Area.* (Lahore: Irrigation Research Institute, 1933).

[35] Thomas, Sir Roger, *Drainage and Reclamation of Irrigated Lands in Pakistan including A Report on Visits to USA and Egypt, 1949.* (Karachi: Times Press, 1949).

[36] Tipton and Kalmbach. *Review of Project Number One Salinity Control Programme in West Pakistan.* (Denver: Tipton and Kalmbach, June 1959).

[37] ——————————. *Feasibility Report on Salinity Control and Reclamation Project Number Two.* (*Chaj Doab*). (Denver: Tipton and Kalmbach, 1960).

[38] ——————————. *Feasibility Report on Salinity Control and Reclamation Project Number 3, Lower Thal Doab.* (Denver: Tipton and Kalmbach, April 1963).

[39] Weir, W. W. *Drainage on Farms*. (Berkely: University of California, Agricultural Experiment Station, 1939).

[40] West Pakistan WAPDA. *Salinity Control and Reclamation Project, Investigations and Background Information* (*Project No. 1*). (Lahore: West Pakistan Water and Power Development Authority, January 1959).

[41] ——————————. *Programme for Waterlogging and Salinity Control in the Irrigated Areas of West Pakistan*. (Lahore: West Pakistan Water and Power Development Authority, May 1961).

[42] ——————————. *Comparison of Cost of Tubewells Installed by WAPDA and Other Agencies*, (*A Note by the Chairman of WAPDA*). (Lahore: West Pakistan Water and Power Development Authority, August 1963).

[43] ——————————. *Progress Report for the Operation of Salinity Control and Reclamation Project No. 1 for the period October 1962 to September 1963*. (Lahore: West Pakistan Water and Power Development Authority, November 1963).

[44] White House, Department of Interior Panel on Waterlogging and Salinity in West Pakistan, *Report on Land and Water Development in the Indus Plain*. (Washington, D.C.: Supdt. Doc., January 1964). This report is referred to as the *Revelle Report* in this paper.