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IRRIGATION SYSTEM ANALYSIS FOR SALT FLUX AND SALINITY BUILDUP IN PUNJAB: RISK ASSESSMENT AND CROP SUSTAINABILITY CONCERNS

M. AZHAR JAVAID AND M. TARIQ YAMIN

Directorate of Land Reclamation Punjab, Irrigation & Power Department Canal Bank Mughalpura, Lahore – Pakistan.

Abstract

The Punjab Irrigation System (PIS) has brought a great prosperity to the province but the induction of salinity and water logging on the other hand, due to salt imbalance, higher seepage losses and low canals delivery efficiency (40%) from canal head to the crop root zone is becoming a great threat to the agricultural sustainability. Irrigation intensity has increased to 122 percent against the overall designed annual intensity of 63 percent. Statistics show that more than 4.5 lac tube wells have been recorded during 1996-97 in contrast to 2.6 lac in 1988-89. More than 70 percent of the tubewells installed to make up the canal water deficit, pump groundwater of marginal to unfit quality and add about 129.06 million tonns (mt) salts. The shallow water table recycling salts further adds 0.14 mt salt load through capillary rise phenomena. The canal and river water, no doubt is excellent in quality but due to restricted drainage contributes about 20.99 mt salts every year (assuming 276 g m^{-3} average salts) through 55.94 million acre foot (MAF) water allocated to the Punjab province. The total salt load to the irrigated soils estimates to the tune of 150.19 mt. The tubewells alone share 85.93%. Consequential to the conjunctive irrigation use after massive deployment of tubewells, the salt balance is no more maintained. Secondary salinity is now becoming a threat and moving towards a dominating position over genetic salinity due to weathering of parent material. Presently about 12.38 percent of the gross canal commanded area is salt-affected and weterlogging has affected another 0.22 percent of the irrigated lands. Salinity has surfaced up as a water short, water excess dilemma. Need is to control the menace. Otherwise it will make our soils unproductive within 80 years or so. Sensing the future course of the agriculture, we must harness our water resources by strengthening the irrigation and drainage capability of the system. Additional water supplies to leach down salts, effective water management endeavors and restricting water rights of the farmer over ground water exploitation may be some interventions to keep a fare salt balance in the Punjab Irrigation Basin.

Introduction

There are about 14 barrages or headworks and 21 main canal systems in Punjab. The total gross command area is 23.35 million acres (basic administrative land unit in Irrigation Department measuring 67 m x 60 m) and culturable command area is 20.81 million acres. The total length of canals is about 37300 km. The length of inter river links is 931 km with off take capacity of 11×10^4 cusec. Overall designed annual intensity of irrigation is 63 percent, while the actual intensity is 122 percent (Akhter, 2000).

Where this system has brought a great prosperity to the nation some problems of salinity and waterlogging have also surfaced up as potential impediments to the agricultural sustainability. In irrigated areas, salinity is almost a universal threat because irrigation waters normally contain hundreds and in extreme cases thousands of mg L^{-1} of salts in contrast to the approximately 10 mg L^{-1} usually found in rain water. The river water used for irrigation in the Indus Plains, although excellent in quality containing about 100 to 200 mg L^{-1} of soluble salts is nevertheless adding nearly 20 million tonnes (100 MAF of water at average salinity of 150 mg L^{-1}) of salts annually over 35 million acres of irrigated lands. Each acre thus receives about 0.6 ton of salts every year (Ahmad and Chaudhry, 1997).

On the other hand forced by the canal water shortage farmers are exploiting groundwater resource on a very large scale, especially at tail ends of the irrigation system (Javaid *et al.*, 1983, Kijne and Vander, 1990). The conjunctive irrigation use of canal and tubewells water began to emerge with time. The groundwater is relatively poor in quality which yielded to salinity and sodicity problems because of its residual alkalinity (Javaid and Younas, 1998), high sulphate contents (Javaid and Ali, 1999) and increased Na/Ca ratios (Javaid, 1998). Sodic soils have been formed in particular where the groundwater high in sodium adsorption ratio (SAR) was applied for crop production (Ahmad, 1990). Thus secondary salinity is becoming a problem.

On an average 13 percent area in Punjab and 25 percent in Pakistan, out of the culturable commanded area, is affected by salinity on the surface. On acreage basis it works out to about 3 million acres in Punjab and 10 million acres in the country (Ahmad and Chaudhry, 1997). With the above situation in view, understanding the irrigation systems developments, the latest position of canal water quality, degree at which the private tubewell developments are taking place and the extent of salinity in major canal commands was considered imperative. The problems may be identified, quantified and rectified to conserve land and water resources and also to impart a prosper future to the coming generations.

Materials and Methods

Water samples from the middle of the canals and rivers were collected from all over the province (Punjab) in clean plastic bottles. The bottles were rinsed 3 to 4 times with the water to be collected and filled to the top and tightly capped. The water samples were collected during May-June from 1998-2000 (premonsonal season) when salts are assumed to be in higher concentration. Thus average results of three years are discussed in the text as one reading. So, to cover maximum risk possibility, the premonsonal sampling was preferred to the postmonsonal sampling under go dilution due to rain flows into the system. The water samples were analyzed for electrical conductivity (EC), major cations (Na, K ,Ca, Mg) and anions (CO_3, HCO_3, Cl, SO_4,) according to the procedures described by Richards (1954). The sodium adsorption ratio (SAR) and residual sodium carbonate (RSC) were worked out as under:

$$SAR= Na/[Ca+Mg/2]^{0.5} \qquad \text{Conc. in mmol}_c\ L^{-1}$$

$$RSC= CO_3+HCO_3-Ca-Mg$$

Total soluble salts (TSS) were calculated as:

$$TSS\ (g\ m^{-3})=EC \times 640, \text{ where: } EC=mS\ cm^{-1}.$$

The TSS in g m^{-3} or ppm multiplied with the factor 0.00136 gives short tonnes (907 kg) of salts added per acre foot (AF) irrigation. The HCO_3/Ca and Ca/Na ratios were also worked out from the data analyzed.

The AF of water pumped by tubewell of one cusec was taken as 1.98 AF/24 hours day. Certain other assumptions (discussed in the text) based on literature explored were also made to work out the SALT BALANCE in the province. The general salt balance equation used in a broad sense was:

$$\text{Salt In } (Cw+Tw+GWs) = \text{Salt Out } (I_L+RF_L+C_R+D_R)$$

Where:

Cw = salts added through canal water

Tw = salts added through tubewell water

GWs = salts added or re-cycled by shallow groundwater table through capillary action (upto 5 meter)

I_L = salts removed from root zone down to soil as a result of normal irrigation

RF_L = salts removed from root zone as a result of effective rainfall / precipitation

C_R = salts removed by crops (+trees) in their produce (straw + grain etc.) as ash

D_R = salts drained outside the soil into drains and rivers.

In this empirical equation, the geochemical precipitation and dissolution of minerals is overlooked to avoid complications.

An extensive literature survey was made to explain the Punjab Irrigation System and groundwater developments in Punjab.

The collections and compilation of the data on salinity is the mandatory role of the Directorate of Punjab Irrigation & Power Dept. The salinity surveys are generally conducted at the level of field or *killa* (measuring 67m x 60m) each year. The salinity surveys are generally conducted during the winter months when salinity is visible on the soil surface. The soil samples are collected at random and analyzed in the laboratories of the Department to support visual observations on salt affected soils.

Finally, the data on river and water quality was statistically manipulated for average values and standard deviations (Steel and Torrie, 1980) in certain cases.

Discussion

The Punjab River System: The Punjab River System (PRS) consists of five main rivers, 1) The Indus 2) The Jehlum River 3) The Chenab River 4) The Ravi River and 5) The Sutlej River. Dams, barrages, head works (H/W), canals and interlinks make a network of PRS. The Indus River enters into Punjab through Tarbela Dam (completed in 1975 with live storage capacity of 9.7 MAF). The Kabul River, the largest tributary of the Indus River and Soan River, another tributary join the Indus River (IR) above Kala Bagh or Jinnah Barrage (constructed in 1946). The Thal canal was taken out from Jinnah Barrage. The Kurram River, another tributary of the IR joins the IR below Jinnah Barrage. Chashma Barrage (completed in 1971 with live storage capacity of 0.7 MAF) and Chashma Jehlum link (CJL) were also constructed in 1970 on the IR (with 21,700 Cs capacity, 63 CM length) as a result of Indus Water Treaty (IWT). The concept was to transfer water to the Jehlum River (and then to feed Rangpur, Haveli and Sidhnai canals). The CJL feeds the Jehlum River downstream Rasul Barrage. Chashma right bank canal is also taken out from Chashma Barrage. Next to Chashma Barrage comes the Taunsa Barrage from where D.G. Khan canal (further dividing into Jampur, Rajinpur and Nur Dhundi canal) from the right bank and M. Garh canal from the left bank are taken out with a Taunsa Panjnad link (completed in 1970 with 12,000 Cs capacity & 38 CM length) that joins below Trimu Head (completed in 1965 with capacity of 650 thousand cfs) after the confluence of Chenab (Chenab – cum – Jehlum) – Ravi River. Then the IR after joining the flow downstream the Panjnad H/W enters into Sindh through Gaddu Barrage.

The Jehlum River (JR) after flowing though Wular lake and collecting water from the Neelum and Kunhar rivers enters Punjab through Mangla Dam, (completed in 1967) from where upper Jehlum canal originates to feed the Chenab River upstreem Khanki Barrage. From Rasul Barrage (completed in

1967 with capacity of 850 thousand cfs) on the JR, Rasul-Qadirabed Link (completed in 1967 with 19,000 Cs and 30 CM length) and lower Jehlum canal (further dividing into Shahpur Branch upstream Faqirian H/W, and Sargodha Northern and Southern Branch from Faqirian H/W) are taken out. The JR then opens into the Chenab River at Trimu H/W, from where Trimu Sidhnai Link (completed in 1965 for a length of 46 CM, discharge of 11,100 Cs), Haveli and Rangpur canals are taken out.

The Chenab River (CR) after flowing through Jammu and Kashmir enters Pakistan (Punjab) in Sialkot District (near Village Diawara). Its flow is regulated through Marala H/W (completed in 1968 with capacity of 1,100 thousand cfs) from where Marala – Ravi Link canal (completed in 1956, discharge 22000 Cs and 64 CM length) falling into Ravi above Shahdara is taken out. The CR below Marala H/W, near Bambanwala H/W divides into Bambanwala-Ravi-Bedian-Depalpur (BRBD) canal to feed Sutlej and Upper Chenab Canal (UCC) to feed Ravi upstream Balloki. The BRBD Link after crossing Ravi Siphon feeds Lahore canal (the extension of former Central Bari Doab, CBDC and Upper Bari Doab of Madhupur H/W, India).

The BRBD also feeds Upper Depalpur canal. After Marala H/W comes the Khanki H/W from where Lower Chenab Canal (LCC) is taken out which after crossing the Qadirabad – Balloki Link (QBL) gives rise to Upper Gogera (Further dividing into Lower Gogera and Burala Branches) at Sagir H/W. Main LCC after passing Sagir H/W receives a feeder from QBL and then divides into Jhang and Rakh Branches. The Q.B.L (completed in 1967 with 80 CM length and 18,600 Cs capacity) is taken out from Qadirabad H/W (completed in 1967 with the capacity of 900 thousand cfs) on the CR. To the CR then joins the Jehlum River at Trimmu H/W.

The water of Ravi River (RR) is regulated through Madhupur H/W in India and in Pakistan it is controlled through Balloki (from where lower Bari Doab Canal, LBDC and Balloki-Sulemanki Link is taken out) and Sidhnai Barrage, (Balloki and Sidhnai both completed in 1965 have a live storage capacity of 225 and 150 thousand csf, respectively) .The MR link and UCC feed the RR upstream Balloki H/W. Balloki – Sulemanki Link (BSL) which after some distance divides into BSL-1 (completed in 1953 with 15,000 Cs capacity and 53 canal mile length) and BSL-II (completed in 1968 with a length of 39 CM and live capacity of 9,000 Cs) is fed at this H/W from QBL . Before joining the main Chenab River (Chenab –cum-Jehlum) down stream the Trimmu H/W, the RR communicates with Trimmu – Sidhnai (TS) and Haveli canal. Sidhnai – Mailsi link (S.M.L) also emerges from the RR. Sidhnai canal is taken out from Sidhnai Barrage. The Jehlum River upstream and the RR downstream the Trimmu H/W joins the Chenab River. Taunsa – Panjnad feeds the Chenab River (Jehlum – cum – Chenab – cum – Ravi) downstream the confluence of Chenab – Ravi River or upstream to Panjnad H/W.

The Sutlej River (SR) on it has Ferozepur H/W in India near International Boundary. In Pakistan Sulemanki H/W regulates its flow. The Depalpur Lower takes off from BSL-I near Ghanda Singh. Both the BSL-I and BSL-II outfall with the Sutlej River above Sulemanki H/W from where Pakpatton canal at right bank and Fordwah and Eastern Sadiqia (further giving out Hakra Branch) at the left bank emanate. Down stream to the Sulemanki H/W, Qaim and Bhawal Canal (further dividing into Desert Branch) emanate from Islam H/W. It also receives Sidhnai-Mailsi Link passing through Mailsi Syphon (completed in 1965 with live storage capacity of 429 thousand cfs) downstreem Islam H/W. Mailsi – Bhawal feeds Bhawal canal at the left bank of the SR. Sidhnai – Mailsi Bhawal link of 62 CM completed in 1965 has a capacity of 10,100 Cs). Mailsi canal giving rise to Lodhran Branch is also a part of this system. The SR joins the Chenab River (Jehlum–cum-Chenab–cum-Ravi) at Panjnad H/W from where Panjnad canal (giving rise to Minchin Branch) and Abbasia canal shoot out. The Indus River joins this Chenab cum other four rivers system downstream Panjnad and then flows as Indus River to Sindh through Gaddu Barrage, a water gateway to the province. For an overview of the Punjab River System, schematic diagram of the main rivers and canals (Fig-1) in Punjab is added as a part of the text. Some physical and hydrological features of the canals are also tabulated (Table 1). However, they are not explained just to avoid the length of the text.

Surface Water Quality: The studies conducted earlier (Eaton, 1953, Asghar, 1960, Nazir, 1961, Chaudhry, 1972, were confined only to the main rivers of the Indus and not upto the canal level. This new study conducted during May-June from1998-2000 also covers the rivers and at the same time aims at the chemical composition of various canal waters. The earlier workers limited to periodic collection and analysis of average river waters only, perhaps they did not observe the post Mangla (1967) or post Tarbela (1975) irrigation regime in context of water quality. The latest position of canal water and river water is discussed in this text.

Chemicals Composition of River Water

EC and Ion Distribution: Data on river water quality (Table-2) indicate that by any standard of quality the Punjab river waters are excellent. In general the river waters have relatively low electrical conductivity (EC) values (0.273±0.06 mS cm^{-1}). Among the cations, Ca^{2+} predominated the Na^{+} ions. The higher Ca^{2+} level of 2.32 $mmol_c$ L^{-1} was recorded in Indus water at Kala Bagh. Indus water had Ca / Na ratio of 4.2:1. Both the cations (Na and Ca) had an average concentration of 0.48±0.33 and 1.77±0.66 $mmol_c$ L^{-1}, respectively. The higher±values of standard deviation pointed out a great variations in the cations distribution in the rivers. The potassium was present but its concentration was averaged as 0.1 ± 0.04. Among the anions relatively more HCO_3 ions were recorded from the River Indus and minimum from the water sample collected from the River Sutlej near Bhawalpur. However comparison of HCO_3 ions with Ca^{2+} ions reveals that in contrast to HCO_3/Ca ratio of 0.9:1 in Indus water, a ratio of 1.6:1 was recorded in the sample of Sutlej River (Fig. 2).

HCO_3 / Ca and Ca / Na Ratio: It is evident from the data displayed via Fig. 2 that unlike higher HCO_3 /Ca ratio, in Sutlej Water more Ca: Na ratios were observed in the waters of Jehlum and Chenab Rivers, while in Sutlej water it did not exceed 0.7:1 against a high Ca/Na ratio of 11.5:1 and 10:1 in Jehlum and Chenab River waters. The waters with low Ca/Na ratio but greater HCO_3/Ca ratio may create salinity and sodicity problem compared to the water with high Ca/Na ratio but low HCO_3/Ca ratio (Javaid, 1998). Low Ca/Na and high HCO_3/Ca ratio is the typical characteristic of the Sutlej water.

The SAR and RSC: It can be observed that even at low Ca/Na ratio, the water of the Sutlej River had a higher sodium adsorption ratio (SAR). The minimum SAR value of 0.17 was noted in the water samples of the Jehlum and Chenab Rivers (Fig.3). However, the River waters showed an average SAR value of 0.52 ± 0.45. The higher standard deviation (± 0.45) almost at par with the average SAR value indicates a great inter-source variability.

The carbonate ions (CO_3^{2-}) are normally absent or found in traces. The bicarbonate (HCO_3) ions, however, predominate the other anions. As a result of higher Ca+ Mg concentrations in the waters in relation to HCO_3 the residual sodium carbonate (RSC=HCO_3+CO_3- Ca-Mg) values are ≤0.0 $mmol_c$ L^{-1}. As far as HCO_3 ions are considered, they did not increase the average value of 1.92 ± 0.47 $mmol_c$ L^{-1}. The average pH noted for river waters fell in the range of 7.5 ± 0.07.

Total Soluble Salts: The data (Fig.3) displayed in bars reveal higher total salt concentration level as high as 236.8 g m^{-3} in Indus water and as low as 147 g m^{-3} in Sutlej water. On the average, river waters have the total soluble salts of 174.9± 36.5 g m^{-3}. The Indus River water thus in its each acre foot water contains about 292 kg total soluble salts, while the same AF water of the Sultej River contains 182 kg soluble salts. The salts contained in the waters of the other rivers fall in between these mentioned range. It will be clear from the data that average soluble salts contained in the canal waters are higher. This depends upon the soil strata and soils geochemical composition through which the canals pass.

Chemical Composition of Canal Waters

The detailed radical distribution and water quality parameters in respect of individual Canal waters are given in Table 3 A & 3 B and Table 4 A & 4 B. Like river water, the canal water quality is the excellent one. However brief view is given here.

Radical Distribution: The data on radical distribution (Table 3 A & 3 B) for all the canals + links and branches indicate that like that of river water, Ca^{2+} dominates the Mg^{2+} and Na^{+} ions having an average concentration of 1.69± 0.53, 0.53 ± 0.40 and 0.73 ± 0.7 $mmol_c$ L^{-1}. The higher standard deviation from the average values in case of Mg^{2+} and Na^{+} indicates a substantive variation in their distribution in different canals taking off from different rivers. The potassium on the average did not exceed 0.1 $mmol_c$ L^{-1} in canal waters. It is worth mentioning that highest Ca^{2+} was detected in the water of D.G. Khan canal. This is perhapse due to the reserve of gypsum in the soils of D.G. Khan. The water runoff into the canals from Hill Torrents may also result in higher Ca^{2+} status of the D.G. Khan canal. This concept is supported by an accompanied increase in SO_4^{2-} anion in the D.G. Khan canal water.

Among the anions HCO_3^{2-} ions dominated the other two main cations, Cl^- and SO^{2-}_4. The average concentration of HCO_3^{2-}, Cl^- and SO_4^{2-} worked out is 1.85 ± 0.70, 0.67 ± 0.61 and 0.52 ± 0.5 $mmol_c$ L^{-1} like $Mg^{2+}$and Na^{+} ions, the higher standard deviation of Cl^- and SO_4 ions from their mean values indicates a viable variation in their distribution: The highest standard deviation value, (even from mean value) in case of SO_4^{2-} indicates higher variability in relation to other anions.

The SAR, Ca/Na and HCO_3/Ca Ratios: The data (Table 4 A & 4 B) give the detailed values of the SAR, Ca/Na and HCO_3/Ca ratio for all the individual canals and branches. Data statistically treated for mean and standard deviation values for the said parameters gave an average values of 0.70 ± 0.6, 5.72 ± 4.6:1, 1 ± 0.3:1. respectively. The higher values of standard deviation values again depict huge difference in their distribution and frequency in the canal waters of different canals studied.

One thing is clear that canal waters have low Na^+ but high Ca^{2+} contents. Compared to the HCO_3 the Ca^{2+} has lower concentration (high HCO_3 /Ca ratio) in the canal irrigation waters.

EC and Total Soluble Salts (TSS): The higher electrical conductivity (EC) values were measured in the Rangpur and D.G. Khan canal water (0.58 and 0.54 mS cm^{-1}, respectively). However, among the link canals, higher EC value of 0.61 mS cm^{-1} was recorded in Chashma – Jehlum Link canal. Corresponding to their EC values higher total soluble salts were calculated for the mentioned canal waters. It is estimated that based on their EC values (EC mS cm^{-1}x640= g m^{-3} or ppm), one acre foot water (43560 ft^3 water) of Rangpur and D.G. Khan canals contains about 457 and 426 kg of total soluble salts. Perhaps this is the reason for frequently occurring of the saline soils in these geographical areas.

On the average the canal water had an EC and TSS corresponding values of 0.30±0.13 mS $cm^{-1}$and 192±83mmol$_c$ L^{-1}. The comparison of canal and river waters reflects that EC and TSS values in the former water source are higher. The salts added to the soils therefore, need to be worked out on the basis of their average values in the canal waters from where the fields are actually getting water.

The results (Table 4, Fig.2) show that both in rivers and canal waters the Ca/Na ratios are also favourable. As high as >12:1 Ca/Na ratio is noted in canal water of LJC in contrast to groundwater (tubewell water), where Na usually dominates the Ca+Mg (Javaid *et al.*, 1999). High Ca/Na ratio in surface waters may be due to the fact that they carry a load of calcareous silt with them. However, HCO_3 concentrations were higher than concentrations of SO_4^{2-} and Cl^- in case of all surface waters. A further comparison of HCO_3/Ca ratio reveals that except in few cases the ratio of HCO_3 to Ca was higher.

The data on river water quality show that Calcium + Magnesium and Bicarbonate ions like canal waters are the dominant constituents in water of the Indus River. This is because the catchment area of the Indus is underlain by rocks, mostly composed of lime stone, sand stone, shale, slate, gneiss, schist, granodiorite and syenite which solubilize and minerals flown as a result of relatively high rainfall. Therefore, the composition of river water depends upon the geology of the area. The northern Himalyian mountains forming the upper catchment drainage of the Indus River and its principal tributaries are mostly underlain by the metamorphic, igneous and sedimentary rocks of Mesozoic to Pre-comparison ages. Sedimentary rocks are composed mainly of limestone, sand stone and shale; where as, metamorphic and igneous rocks are mainly composed of slate, granite, gneiss, schist, granodiorite and syenite (Chaudhry, 1972). Thus in an area where lime stone and dolomite dominate, the water would have higher Ca+Mg and carbonates in contrast to the one having catchment area in salt range where Na and Cl will dominate.

We have observed that CO_3^{2-} (carbonate) is absent and HCO_3^- (bicarbanate) present in the surface waters. Actually, where there is abundance rainfall and much organic matter (as is in northern catchment area) in the soil, the groundwater becomes significantly charged with CO_2. As a result, CO_3 material dissolves to form HCO_3 which dominates in stream flow and are in excess over SO_4^{2-} and Cl^-. However, in arid regions, SO_4^{2-} and Cl^- ions tend to prevail in surface water and Na^{1+} also becomes equivalent or in excess to Ca^{2+}.

Finally, it can be concluded that concentration of salts in runoff depends upon the composition and physical properties of rocks and soils in the catchment area with which the water comes in contact and the duration of contact. The more insoluble rocks underlying a drainage basin and catchment area the smaller are the influences of geology and groundwater on the chemical quality of the surface water (Chaudhry, 1972).

Finally, it is observed that water quality of rivers and canals varies with the sampling point, environmental changes in climate (rainfall and temperature), truncation of canal banks and catchment area, time and season (temporal variation), and the variation in the stream flow also affects the composition of waters The effect of variation in stream flow and time of sampling on cations and anions distribution in Indus River water is shown in Fig. 4 that is being reproduced (Chaudhry, 1972) for the interest of the researchers.

Conjunctive Irrigation Use

Forced by the canal water scarcity, especially at tail reaches of the canal commands, the farmers are exploiting the groundwater resource. Conjunctive irrigation use in different forms began to emerge. Statistics show (Table 5) that about 264776 tubewells were installed in Punjab during 1988-89. Out of this, 10219 by public, while 254557 were installed in private sector. In 1996-97, the number of tubewells was 70.9% higher to the base year (1988-89). It is clear that compared to the public, more tubewells were installed in private sector. Tubewells unluckily, pump water of poor to marginal quality. It is reported that 70% of discharge of the existing wells is saltish (Anonymous, 1995, Malik *et al.*, 1984).

The data (Table 6) reveal that area irrigated by tubewells and canal was 2170 and 4405 thousand hectares in 1988-89 that turned to 2411 and 3920 thousand hectares during 1996-97. It shows the increase in tubewells irrigated area and decrease in canal served area. Similarly, 5527 thousand hectares were irrigated conjunctively by canal and tubewells in 1988-89, while it increased to about 6325 thousand hectares in 1996-97. No doubt, conjunctive irrigation use is considered an effective solution that ensures viability of irrigated agriculture. But injudicious use of poor quality groundwater even by applying it in conjunction with canal water is inducting salinization and sodication in irrigated soils. Over extraction of the groundwater also has given rise to deep water table and intrusion from saline to fresh aquifer. It is worth mentioning that so for, there are no legal rights or restrictions framed or regulations defined for the extraction of groundwater resource. The surface water resources if not harnessed and tapping of groundwater resources on that large scale if continued, the soil degradation through salinization and sodification would not be uncommon.

Water Quality – New Concerns

The pumped groundwater is mixed with canal water (surface water) to bring the limits of conventional water quality indicators (EC, SAR and RSC) down to the permissible levels. The experience has shown that information on the conventional water quality indicators alone is not sufficient to decide its potential use for crop production and soil health. Some tubewells withpermissible SAR and even negative RSC status sodicated the soil on their long term use (Javaid & Ali, 1999).

The RSC accounts for Calcite precipitates only, ignoring the precipitation of Ca^{2+} with SO_4^{2-} as gypsum, especially when RSC is negative (Ca is there). Similarly Mg^{2+} precipitates as sepiolite [Mg Si_3O_6 (H_2O)] on concentrating of the soil solution, thereby sodicating the soil through elevating the relative activity of sodium (Marlet, 1998). Thus, geo-chemical processes taking place in soil-water system need to be investigated in the context of groundwater use. Perhaps, this is one of the many reasons for that salinity is increasing in irrigated areas of Pakistan's Punjab where evapotranspiration potential is high.

Soil Salinity in Canal Commands

Soil salinity is the most serious problem affecting irrigated agriculture and limiting crop production over the large tracts of Punjab. It is a recognized fact that major damage due to salinity problem occurs in agricultural sector, where crop productivity is either completely eliminated or is greatly reduced (Ahmad & Chaudhry, 1997).

The data (Tabe 7) indicate that canal commanded area of Fordwah is affected to a great extent (32.40%) followed by Rangpur, Haveli, and M. Garh canals which respectively have 25.87, 24.98 and 22.98% salt affected area. Fordwah is affected to a great extent (32.40%) followed by Rangpur, Haveli, and M. Garh canals which respectively have 25.87, 24.98 and 22.98% salt affected area.

The data on waterlogging show that 1.24% of the CCA of Eastern Sadiqia is waterlogged with 13.99% salinity spread-up, while 32.40% CCA of Fordwah is salinity beaten with 0.84% waterlogged area.

The reason of salinity spread up in Fordwah may be attributed to the brackish sub-soil water, being pumped by the farmers. Another reason is re-distribution of the salts through shallow sub-soil water as a result of high evapotranspiration potential in the region. The same happened in Eastern Sadiqia, where watertable and saline sub-soil water caused salinity build up to the extent of 13.99% with 1.24% area with shallow watertable (waterlogged).

The groundwater use of marginal to unfit quality for crop production in Rangpur canal commands may be the potential reason of salinity.

The salinity spread-up in D.G. Khan canal command may be due to arid climate (high evapotranspiration potential moving salts upward) characteristics of high temperature and low rainfall with mean annual rainfall of 81.00 mm (WAPDA, 1993). Another reason is seepage induced waterlogging from the Indus river, seepage from canal system and ponding of water of Hill Torrents from Koh-i-Suleman Range (The sub-soil water is marginal and hazardous (mostly). Mineralization of groundwater generally increased with depth in D.G. Khan (WAPDA, 1993). Thus exploitation of groundwater has induced the problem.

The other possible reasons of salt accumulation responsible for salt distribution are, 1- salt existing in the soil before irrigation system was introduced (genetic salinity) 2- salts added through irrigation (canal and tubewell waters) which does not properly meet with irrigation and leaching requirements of soils (secondary salinity) and 3- addition of salt residues to the upper soil layers by capillary action where poor quality sub-soil water (or even normal water containing salts from soil it is saturating) is shallow. The analysis of the facts reveals that secondary salinity is now becoming a threat and is moving towards a dominating position over genetic salinity due to weathering of parent material. Finally, the Soil Survey of Pakistan (Chaudhry, 1979) warned about the imminent threat of salinization through the use of poor quality groundwater by public and private tubewells. The often doubtful quality of groundwater was known for much longer, but it became an important issue due to the massive deployment of tubewells in the irrigation system (Kuper, 1997). It is also pointed out that the gross area reported in table 1 and that given in table 7 varies besides the fact that both are reported by the different sections of the Irrigation Department. It accentuates the need to coordinate the activities on sound footings.

Salt Balance and Salinity Status

Actually, any element contributing towards imbalance in the salt balance equation would be responsible to salinity or sodicity induction. However, the gravity of the problem depends upon the antropy of the disturbing element. In different regions sometimes one element/factor may be predominating the other elements of the salt balance equation i.e. already explained in section on materials and methods in the following form:

$$\text{Salt In } (Cw+Tw+GWs) = \text{Salt Out } (I_L+RF_L+C_R+D_R)$$

Tentative calculations for salt balance may be made on the basis of some assumptions often made by many workers. Various components of salts balance are discussed below.

Salt Addition through Canals Water (Cw): Taking 276 (193±83)gm^{-3} (ppm)as total soluble salts (upper limit) present in canals, approximately 0.8 tonns of salts are added to every acre receiving an average of 2AF irrigation in a year (g m^{-3} x 0.00136=t/AF). In 55.94MAF water allocated to Punjab (37.07 in *Kharif* and 18.87 in *Rabi*) a total of 20.99 million tonns of salts are added.

Salt Addition through Tubewell Water (Tw): Similarly, according to a recent estimate tubewells in Punjab upto 1996-97 in public sector are 8122 and those in private sector are 444309 in number. If public tubewells are considered to contain on the average 1000 g m^{-3} slats (actual salts contents may vary from 1000 to 3000 g m^{-3}) and supposed to run for 260 days / year at the rate of 2.5 cusecs, then the salts added would be.

8122x2.5x1.98x260x1000x0.00136=14.21 million tonn/year.

Similarly, 444309 farmers' tubewells (1cusec mostly) running for 120 days/year having an average EC of 1.25 mS cm^{-1} (800 g m^{-3}) will add salts.

444309x1.0x1.98x120x800x0.00136=114.85 million tonn/year.

Salt Addition through Ground Water (GWs): The salts contributing from groundwater (at the average depth of 5 feet water table) through capillary action @ 24 inches evaporation per year (water evaporation from the free water surface is estimated by the Directorate to be 65 inches, generally, shallow the water table more will be the evaporation and vice versa) can be estimated @ 1000gm m^{-3} salts in the waterlogged area of about 51228 acres in Punjab i.e.

51228x1000x0.00136x2=0.14 million tonn/year

Thus in total about 150.19 million tonns salts are added to the Punjab land system each year. Thus new worked out figure varies from that of Ahmed (1995) who quoted in his revised edition as 71.15 million tonns when deployment of private tubewells did not exceed 220 thousand. The data of tubewells (Table 5), now show increasing trend of private tubewells and decreasing one in public tubewells, now being denotified for the water quality havoc they are playing with and high O & M cost etc.

Recently all the SCARP tubewells in fresh zone have been transitioned or handed over to the farmers through Punjab Groundwater Development Project.

Salt Removal by Leaching at Normal Irrigation (I_L): Now, for the salts removal, it is assumed (based on 25% water percolation losses) that 25% of the salts added to the fields are removed by leaching (25% percolation meets 25% leaching requirement as a thumb rule). The 25% (37.51 m tonns) of the 150.05 m tonns salts added by canal and tubewells irrigation will leach down the root zone.

Salts Removal through Effective Rainfall (RF_L): The rainfall varies with the geographic distribution of the area. If the annual average precipitation is assumed to be 10- inches and 5 inches of it are considered as effective precipitation (0.42 AF), then it will provide 21% leaching requirement of the assumed average water application per acre of 2 AF per year i.e.(0.42 x 100/2). It will further remove through leaching about 21% (23.63 million tonns) of the salts left (112.54 million tonns) after 25% removal through irrigation (37.51 million tonns) to the fields. Total salts removed through leaching (by irrigation and rainfall) amount to 61.14 million tonns).

Salt Removal by Drainage (D_R): Punjab has a network of drains and their systems such as Raniwah and Mona drain systems of Chaj Doab (area between two rivers, Chenab and Jehlum). Industrial effluents, tubewells pumping water directly into drains and those removed from upland area and drainage projects act as major sources of salts. Besides contaminating the groundwater resource, the drains communicate with the Sea, creating a water quality concern. The salts removed (SR) by drainage can be estimated as under:

SR = Salts in Indus at Kalabagh–Salt in Indus upstream Gaddu Barrage.

The soluble salt contents in the Indus River at Kalabagh are estimated 140 g m^{-3} (average). However, the salts vary from 151 to 237 g m^{-3} during different calender months, being highest during June. The annual discharge at Kalabagh on average basis (1927-97) is estimated 89.65 MAF (Chandio & Aftab, 1999). Salts thus can be estimated through equation:

140x0.00136x89.65=17.1 mt

The average salt contents at the point where all the rivers join the Indus (Gaddu upstream) estimate to 260 g m^{-3}. Taking care of Kalabagh withdrawal (5MAF) and Chashma + Jehlum and Taunsa – Panjnad withdrawals (5.55 MAF) to meet about 10.5 MAF water deficit of Punjab (Jehlum and Chenab at Mangla and Marala have an annual flow of 23.3 and 25.9 MAF), the average annual flow is estimated 95 MAF. It includes about 30 MAF water lost every year to the Sea below Kotri Barrage. The salts at this point would be:

260x0.00136x95=33.6 mt

The soluble salts removed by the drainage process through Punjab River System are 33.6-17.1=16.5 mt (It excludes the salts precipitated).

Biological Salt Removal (C_R): Data on salt removed by the major crops (Table 8) show that approximately 2.95 mt salts (as ash) are removed. Salts removal by fruit and forest trees and fodder crops are not considered. However, rough estimation based on salts removal per acre (that can be calculated from the referred table on crops) shows that vegetables + fodder remove salts @ 0.3 t ha^{-}

^{1} while the trees account for 0.08 t ha^{-1} in a year. The area multiplied with the salt removal can give the tentative estimate.

It is clear from the aforementioned discussion that the outgoing salts amount to 80.59 mt (61.14+16.5+2.95 removed by irrigation + rainfall, drainage and crops, respectively), while the addition of salts through canal water, groundwater extraction and shallow water table amounts to 150.19 mt. This gives a net addition of 69.60 mt of salts to the Punjab Irrigation Basin.

The disturbed salt balance is giving rise to Secondary Salinity, which is now gaining a dominant position over the genetic salinity. The salt-balance mechanism if not properly managed, it will turn our most of the irrigated lands unproductive within 80 years or so. Need therefore, be felt to look into the balance and adopt such means and ways that can effectively control the problem without serious quality concerns to the system.

Conclusions and recommendations

The following tentative and general conclusions and recommendation can be drawn from this study.

1. Punjab Irrigation Systems (PIS) large scale irrigation developments have brought great prosperity to the people but it also mobilized salts and yielded to salinity and waterlogging problems.
2. Salinity / sodicity has surfaced up as water short, water excess dilemma due to defective management at various levels and for economic reasons. At present about 12.38 % of the CCA is salt affected and 0.22% waterlogged.
3. Canal water is excellent in quality. It has low Na/Ca but high HCO_3/Ca ratios. Besides its excellent quality, canal water is adding salts to the basin because of restricted drainage.
4. About 150.19 mt salts are added while 80.59 mt are removed per year. Net addition of 69.60 mt per year thus may become a concern in future. Thus salt balance is disturbed and requires attention of the irrigation managers.
5. The irrigation water applied should take care of both crops and leaching requirements.
6. The measures should be taken to lower down the shallow water table.
7. Drainage effluent loaded with salts should not be directly unloaded to the rivers furnishing water to the canals for irrigation purpose. The re-use potential of drainage surplus should be assessed.
8. Rights of farmers over groundwater exploitation should be defined to prevent over pumpage and intrusion from saline zone to the fresh water zone.
9. Water storage or reservoirs need immediate construction to minimize dependence on groundwater of poor to marginal quality. Otherwise, forced by the canal water shortage, the farmers would continue the practice of exploiting poor water quality ground water.
10. Adequate knowledge on water quality is must. The water with low Na/Ca but high HCO_3/Ca ratio or waters of even negative RSC may sodicate the soil through geochemical precipitation process.
11. Unless the surface water resources are not harnessed, the use of spatio-temporal salinity and ground water database should be made effectively in developing targeted reclamation programmes in canal commands.

12. There should be tremendous coordination between different quarters of the Irrigation Department to achieve higher work standards.
13. The NDP (National Drainage Programme) should be effectively launched to export salts from soils to get rid of the problem.
14. Groundwater legal regulatory framework should be implemented with sincerity.
15. A sound groundwater resource picture should be developed and aquifer quantified in terms of its time scale depletion at the existing pumping rate.

Table 1. Different features of existing river – canal system of Punjab.

S. No.	Canal	Year of const.	CCA/G.A 000 acres	Designed intensity P/NP	Water allowance P/NP	Discharge capacity (000 Cs)	Length (CM) Main	Total*
1	Upper Jehlum	1915	544/613	45-80/50	3.03/3.25	8 7	88.0	730.8
2	Lower Jehlum	1901	1518/1616	45-70/70	2.84/4.30	5.3	39.4	1566.4
3/4	Upper Chenab/BRBD	1912/1956	1441/1563	60/31-46	2.73/2.93	16.5/7.2	42.8	1593 9
5	M.R. Link (Int)	1956	158/175	-/-	-/-	1.4	-	189 9
6	L. Bari Doab	1859	659/709	75-100/-	3.22/-	2.5	-	804.6
7	Lower Chenab	1892	3054/3698	50-75/46	3.17/4 3	11.7	155.9	2984.1
8	LBDC	1913	1670/1789	60-67/66	3.0/3.3	9.2	129 9	1522 0
9	U.Depalpur	1928	350/384	-/60	-/5.5	2.4	52.9	481.2
10	Pakpattan	1927	1049/1177	54-60/70	3.6/5.5	5.2	183.1	1143.2
11	M/Garh	1958	820/928	-/70	-/6 36	8.9	74.2	1053.0
12	Thal	1947	1912/2219	70/-	3.8/-	7.5	31.5	2120 1
13	Rangpur	1939	345/358	-/70	-/4.8	2.7	138.2	523.3
14	D.G. Khan	1958	906/957	-/70	-/6.36	8.3	69.0	1118.4
15	Panjnad	1929	1355/1532	80/70	4.2/5.5	10.4	57.2	1640 3
16	Abassia	1929	154/296	80/70	4.25/5 5	1.3	25.7	168 4
17	Bahawal	1927	730/733	80/70	2.5-4/5.5	4 4	17.9	676.0
18/19	Qaim/Mailsi	1927/1928	1036/1098	-/60	-/5.5	0.5/4.9	33.0	983.2
20	E Sadiqia	1926	1052/1172	80/-	3.6/4.5	5 8	49.0	903.2
21	Fordwah	1927	428/561	80/60	3.6/5.5	3.4	9.2	506.2
22	L. Depalpur	1928	612/654	-/60	-/5.5	4 0	6 4	779.0
23/24	Sidhnai Canal/Haveli	1886/1939	1017/1166	60-80/60	3/4.8	4.0/5.2	36.4	1145 2

CCA = Canal commanded area, G.A = Gross area , P = perennial, NP = Non-perennial , Cs = cusecs, CM = Canal mile.

* Total length includes length of branches, sub branches, distributaries and minors

Note. The original sequence of canals is changed in conformity with the T & SS statement of the DLR

Table 2. Chemical composition of river waters (average of 3 years).

River	pH	EC mS cm^{-1}	Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}	Salt contained by the river Water (Kg/AF)
			mmol$_c$ L^{-1}							
Indus at Kalabagh	7.5	0.370	2.32	0.75	0.54	0.10	2.21	0.50	1.00	292
Jehlum at Mangla	7.4	0.273	2.30	0.20	0.20	0.03	2.20	0.30	0.23	216
Chenab at Marala	7.5	0.232	1.80	0.32	0.18	0.02	2.00	0.22	0.10	183
Ravi at Shahdra	7.5	0.262	1.72	0.31	0.48	0.11	2.10	0.33	0.19	207
Sutlej at B Pur	7.6	0.230	0.70	0.50	1.00	0.10	1.10,	1.00	0.20	182

Note: Carbonate (CO_3^{2-}) was absent or detected in traces, RSC of all the samples was ≤0 mmo

Table 3 A. Radical distribution in waters of main canals (average of 3 years).

S. No.	Canal	Sampling point	Discharge Cs 000	Ca^{2+}	Mg^{2+}	Na^{1+}	K^{+}	HCO_3^-	Cl^-	SO_4^{2-}
						mmol$_c$ L^{-1}				
1	U.J.C	At Mangla	8.7	2.1	0.3	0.2	0.06	2.3	0.1	0.26
2	L.J.C	At Rasool	5.3	2.3	0.2	0.2	0.03	2.2	0.3	0.23
3	U.C.C	At Marala	16.5	1.4	0.8	0.2	0.1	1.9	0.1	0.5
4	M.R. Link (Int)	Talvindi	1.4	1.3	0.6	0.3	0.1	1.8	0.2	0.3
5	B.R.B.D	Near Jallo,Lhr.	7.2	1.5	0.2	0.2	0.1	1.5	0.3	0.2

6	L.C.C	At Chakanwali	4.7	0.8	0.2	0.1	0.1	0.7	0.4	0.1
7	C.B.D.C	At Mughalpura	2.5	1.1	0.2	0.3	-	0.9	0.4	0.3
8	L.B.D.C	At 112/15-L, M.C	9.2	1.8	0.5	0.6	0.1	2.0	0.7	0.3
9	L. Depalpur	Near Ganda Singh	4.0	1.6	0.7	0.8	0.1	2.1	0.7	0.4
10	Pakpattan	10 km down- stream S/H	5.2	1.5	0.6	1.3	0.2	1.8	1.0	0.8
11	Mailsi	Near Mailsi Syphon	4.9	1.6	0.7	1.4	0.2	2.0	1.0	0.9
12	Haveli	Near DLR Farm	5.2	2.0	0.8	1.8	0.1	2.3	0.3	2.1
13	M. Garh	-	8.9	-	-	-	-	-	-	-
14	Thal	Near Layyah	7.5	2.1	0.7	0.5	0.1	2.4	0.3	0.7
15	Rangpur	Near Town	2.7	2.2	0.4	3.1	0.1	2.4	3.0	0.4
16	D.G. Khan	Near D.G. Khan	8.3	2.8	0.6	2.1	0.1	2.9	0.6	1.9
17	Punjnad	Punjand H/W	10.4	1.2	0.8	1.4	0.2	1.6	1.1	0.9
18	Abassia	5km downstream Punjnad	1.3	1.7	0.5	0.4	0.2	2.0	1.1	0.7
19	Bahawal	10km downstream B/Pur	4.4	0.7	0.5	1.0	0.1	1.1	1.0	0.2
20	Qaim	Near Bahawalpur	0.5	2.0	1.5	1.9	0.4	2.8	2.5	0.5
21	E. Sadiqia	Near Bahawalnagar	5.8	1.7	-	1.0	0.1	2.0	0.8	-
22	Fordwah	Near Fordwah	3.4	1.7	0.1	0.9	0.1	1.5	0.9	0.4

U.J.C= Upper Jehlum Canal, L.J.C = Lower Jehlum Canal, U.C.C = Upper Chenab Canal, B.R.B.D = Bambanwala Ravi Bedian Depalpur, L.C.C = Lower Chenab Canal, C.B.D.C = Central Bari Doab Canal (Lhr. Canal), Cs = Cusec. M.R.L. = Marala Ravi Link, L.B.D.C = Lower Bari Doab Canal, DLR = Directorate of Land Reclamation, M.C = Mian Channun, S/H = Sulemanki Head works, Upper Depalpur has a discharge of $2.4x10^3$ cusec, M.R. Link has $22x10^3$ Cs. at the heads.

Table 3 B. Radical distribution in waters of some other link canals and branches (average of 3 years).

S. No.	Canal	Sampling point	Discharge Cs 000	Ca^{2+} SO_4^{2-}	Mg^{2+}	Na^{1+}	K^+	HCO_3^-	Cl^-	
						mmol L^{-1}				
1	Chashma Jehlum L	6 km down- stream B	21.7	1.6	1.9	2.4	0.2	3.4	1.0	1.5
2	Rasul-Qadirabad L	8 km down-stream Rasool	19.0	2.3	0.2	0.2	0.03	2.2	0.3	0.2
3	Rasul barrage on Jehlum	1km downstream Rasool (B)	-	2.6	0.1	0.2	0.03	2.1	0.3	0.5
4	L.J.C. (N) Branch	Near Sargodha	-	2.6	0.1	0.3	0.03	2.3	0.4	0.3
5	L.J.C. (S) Branch	Near Sargodha	-	2.3	0.3	0.3	0.03	2.4	0.5	0.03
6	Trimmu-Sidhani L	Near Shorkot Farm	11.1	1.9	0.4	1.7	0.1	1.1	1.4	1.6
7	L.C.C	At Sagir H/W	-	1.2	-	0.1	-	0.8	0.4	0.1
8	Upper Gogera (L.C.C)	6 Km downstream Sagir H/W	-	1.4	0.4	0.1	-	1.2	0.3	0.4
9	Lower Gogera (L.C.C)	Near Jaranwala	-	1.2	0.2	0.2	0.10	1.3	0.2	0.2
10	Burala Br (L.C.C)	Near Jaranwala	-	1.3	0.7	0.1	0.1	1.5	0.5	0.2
11	Rakh Br. (L.C.C)	15 Km down- stream Sagir H/W	-	1.2	-	0.3	-	1.0	0.4	0.1
12	Jhang Br. (L.C.C)	20 Km down- stream Sagir Head	-	0.7	0.3	0.2	0.1	0.7	0.6	-
13	U.C.C	Faqir Pura, GRW	16.5	2.2	1.2	0.2	0.1	3.5	0.1	0.1
14	U.C.C	Chicher wali, GRW	16.5	1.9	0.6	0.2	0.1	2.0	0.5	0.3
15	U.C.C	Rata Bajwa GRW	16.5	1.3	0.2	0.1	-	1.0	0.5	0.1

L.J.C = Lower Jehlum Canal, L.C.C = Lower Chenab Canal, U.C.C. = Upper Chenab Canal, GRW = Gujranwala, H/W Head works, L = Link, Cs = Cusec (1ft^3/sec water volume passing a point

Table 4 A. Water quality parameters of main canals (average of 3 years).

S. No.	Canal	Sampling point	Disch-Arge Cs 000	PH	EC mS cm^{-1}	SAR -	TSS g m^{-3}	Salt kg /AF* Irri. Water	Ca/Na Ratio	HCO_3/Ca Ratio
1	U.J.C	At Mangla	8.7	7.4	0.26	0.2	166	205	11:1	1:1
2	L.J.C	At Rasool	5.3	7.5	0.27	0.2	173	213	12:1	1:1
3	U.C.C	At Marala	16.5	7.9	0.25	0.2	160	197	7:1	1.4:1
4	M.R. Link	Talvindi	21.4	8.1	0.23	0.3	147	181	4:1	1.4:1
5	B.R.B.D	Near Jallo,Lhr.	7.2	7.8	0.20	0.2	128	158	8:1	1:1
6	L.C.C	At Chakanwali	4.7	8.4	0.12	0.1	77	95	8:1	0.9:1
7	C.B.D.C	At Mughalpura	2.5	8.2	0.16	0.4	102	126	4.1	0.8:1
8	L.B.D.C	At 112/15-L, M.C	9.2	8.3	0.30	0.6	192	237	3:1	1:1
9	L. Depalpur	Near Ganda Singh	4.0	8.1	0.32	0.8	204	251	2:1	1.3:1
10	Pakpattan	10 km down stream S/H	5.2	8.6	0.36	1.3	230	283	1:1	1.2.1
11	Mailsi	Near Mailsi Syphon	4.9	8.6	0.39	1.3	249	307	1:1	1.3:1
12	Haveli	Near DLR Farm	5.2	7.6	0.47	1.5	301	371	1:1	1.2:1
13	M. Garh		8.9	-	-	-	-	-	-	-
14	Thal	Near Layyah	7.5	7.5	0.34	0.4	218	269	4:1	1:1
15	Rangpur	Near Town	2.7	7.6	0.58	2.7	371	457	0.7:1	1:1
16	D.G. Khan	Near D.G. Khan	8.3	8.0	0.54	1.6	346	426	1:1	1:1
17	Punjnad	Punjand H/W	10.4	8.4	0.36	1.4	230	283	0.9:1	1.3:1
18	Abassia	5km downstream Punjand	1.3	8.5	0.38	1.3	243	300	1:1	1.2:1
19	Bahawal	10km downstream B/Pur	4.4	8.5	0.23	1.3	147	181	0.7:1	1.6:1
20	Qaim	Near Bahawalpur	0.5	8.5	0.58	1.4	371	457	1:1	1.4:1
21	E. Sadiqia	Near Bahawalnagar	5.8	8.4	0.28	1.1	179	221	2:1	1.2:1
22	Fordwah	*Near Fordwah*	3.4	8.6	0.28	0.9	179	221	2:1	0.9:1

*kg salt per acre foot of irrigation = g m^{-3} x 0.00136 x 907. The g m^{-3} and mS cm^{-1} are numerically equal to ppm and dS m^{-1}, respectivlly. Cs = Cusecs, U.J.C = Upper Jehlum Canal, L.J.C = Lower Jehlum Canal, U.C.C. = Upper Chenab Canal, M.R = Marala Ravi, B.R.B.D = Bambanwala Ravi – Bedian – Depalpur, L.C.C = Lower Chenab Canal, C.B.D.C = Central Bari Doab Canal, L.B.D.C = Lower Bari Doab Canal, D.G. Khan = Dera Ghazi Khan, H/W = Head work.

Table 4 B. Water quality parameters of some other links, canals and branches (average of 3 years).

S. No.	Canal	Sampling point	Disch-Arge Cs 000	pH	EC mS cm^{-1}	SAR -	TSS g m^{-3}	Salt kg /AF* Irri. Water	Ca/Na Ratio	HCO_3/Ca Ratio
1	Chashma Jehlum L	6 km down- stream B	21.7	7.5	0.61	1.8	390	481	0.7:1	2:1
2	Rasul-Qadirabad L	8 km down- stream Rasool B	19.0	7.6	0.27	0.2	173	213	12:1	1:1
3	Rasool barrage on Jehlum	1km downstream	-	7.6	0.29	0.2	186	229	13:1	0.8:1
4	L.J.C. (N) Branch	Near Sargodha	-	7.6	0.30	0.3	192	237	9:1	0.9:1
5	L.J.C. (S) Branch	Near Sargodha	-	7.6	0.30	0.3	192	237	8:1	1:1
6	Trimmu-Sidhani L	Near Shorkot Farm	11.1	7.5	0.40	1.6	256	315	1:1	0.6:1
7	L.C.C	At Sagir H/W	-	8.2	0.13	0.1	83	102	12:1	0.7:1
8	Upper Gogera (L.C.C)	6 Km downstream Sagir H/W	-	7.5	0.19	0.1	122	150	14:1	0.9:1
9	Lower Gogera (L.C.C)	Near Jaranwala	-	7.9	0.17	0.2	109	134	6:1	1:1
10	Burala Br (L.C.C)	Near Jaranwala	-	8.0	0.22	0.1	141	174	13:1	1.2:1
11	Rakh Br. (L.C.C)	15 Km down- stream Sagir H/W	-	8.2	0.15	0.4	96	118	4:1	0.8:1
12	Jhang Br. (L.C.C)	20 Km down- stream Sagir Head	-	8.9	0.13	0.3	83	102	4:1	1:1
13	U.C.C	Faqir Pura GRW	16.5	7.8	0.37	0.2	237	292	11:1	1.6:1
14	U.C.C	Chicher wali GRW	16.5	8.1	0.28	0.2	179	221	10:1	1:1
15	U.C.C	Rata Bajwa GRW	16.5	7.6	0.16	0.1	102	126	13:1	0.8:1

*Kg salt per acre foot of irrigation = g m^{-3} x 0.00136 x 907.g m^{-3} and mS cm^{-1} are numerically equal to ppm and dS m^{-1}, respectively. Cs=Cusecs. L.J.C = Lower Jehlum Canal, L.C.C = Lower Chenab Canal, U.C.C = Upper Chenab, H/W = Head work, B = Barrage, L = Link , GRW = Gujranwala.

Table 5. Installation trend of tubewells to exploit groundwater resource in Punjab (Source Directorate of Agriculture Crop Rep. Services Punjab, Lhr.).

Year	Private	Government	Total
1988-89	254557	10219	264776
1989-90	272324	10530	282854
1992-93	318609	9652	328261
1994-95	406080	9191	415271
1996-97	444309	8122	452431

Table 6 Area irrigated through canals (C), Tubewells (TW) and C+TW (000 ha) in Punjab (Source: Bureau of Stat., Pb., Lhr, 1998).

Year	Canal (C)	Tubewells (TW)	C+TW	Total*
1988-89	4405	2170	5527	12342*
1989-90	4327	2263	5722	12538
1992-93	4067	2259	5965	12560
1994-95	3939	2371	6137	12697
1996-97	3920	411	6325	12954

* It includes the area irrigated by wells, canal wells and others.

Tale 7 Surface salinity in different canal commands of Punjab (1998-99)

S. No.	Canal	Gross area reported (acres)	*Thur**	*%Thur*	*Sem***	*%Sem*
1.	U.J.C	572846	20236	3.53	1941	0.33
2.	L.J.C	1574440	275459	17.49	8219	0.52
3.	U.C.C	1423066	212415	14.92	408	0.02
4.	M.R.L	175425	-	-	-	-
5.	B.R.B.D	72943	-	-	-	-
6	L.C.C	3627827	465065	12.81	9937	0.27
7.	C.B.D.C	703013	36108	5.13	978	0.13
8.	L.B.D.C	1721327	171214	9.94	2847	0.16
9.	Depalpur	1008123	133219	13.21	-	-
10.	Pakpattan	1424700	109600	7.69	-	-
11	Mailsi	750977	82714	11.01	-	-
12.	Haveli	1132998	282823	24.98	1772	0.15
13.	M. Garh	851224	195624	22.98	3020	0.35
14.	Thal	2333560	7081	0.30	2617	0.11
15.	Rangpur	356739	92291	25.87		-
16.	D.G. Khan	953881	123223	12.91	267	0.02
17.	Punjnad	1520238	279486	18.38	-	-
18.	Abbsia	302657	24546	8.11	-	-
19.	Bhawal	922364	34612	3.75	-	-
20.	Qaim	45269	7086	15.65	-	-
21.	E. Sadiqia	1228727	171906	13.99	15287	1.24
22.	Fordwah	464840	150638	32.40	3935	0.84
23.	Small Dams	38560	-	-	-	-
24.	Civil Canal	13599	-	-	-	-
	Total of Punjab	23219343	2875346	12.38	51228	0.22

**Thur* is wide term used in Irrigation Department to denote all types of salt – affected soils.

** *Sem* is local terms used for waterloged soils.

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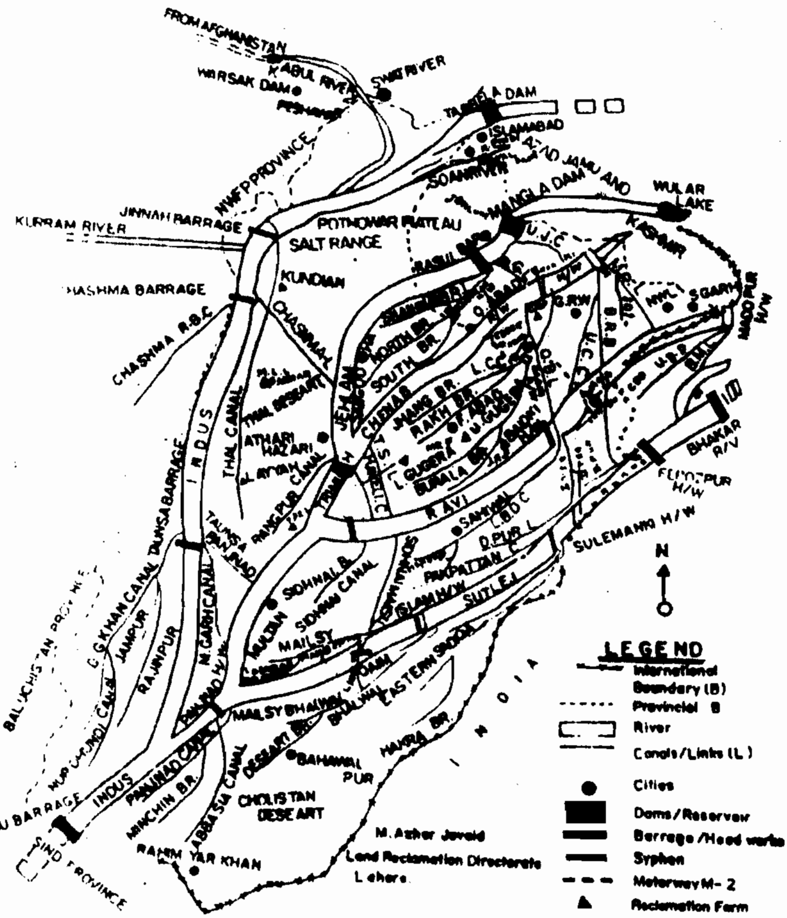

FROM AFGHANISTAN
KABUL RIVER
WARSAK DAM
SWAT RIVER
TARBELA DAM
ISLAMABAD
NWFP PROVINCE
SOAN RIVER
AZAD JAMU AND
MANGLA DAM
WULAR LAKE
KASHMIR
JINNAH BARRAGE
KURRAM RIVER
POTHOWAR PLATEAU
SALT RANGE
KUNDIAN
CHASHMA BARRAGE
CHASHMA R.B.C.
CHASHMA J
INDUS
THAL CANAL
THAL DESERT
ATHARI HAZARI
JEHLAM
CHENAB
SOUTH BR.
JHANG BR.
RAKH BR.
L. GUGERA
BURALA BR.
RAVI
SAHIWAL
L.B.D.C
D.PUR
PAKPATTAN
SULEMANKI H/W
BHAKAR
TAUNSA BARRAGE
DG KHAN CANAL
JAMPUR
RAJANPUR
M.GARHCANAL
PANJNAD CANAL
SIDHNAI CANAL
MULTAN
MAILSY
ISLAM H/W
SUTLEJ
EASTERN SADIQIA
HAKRA BR.
BAHAWALPUR
DESERT BR.
ABBASIA CANAL
MINCHIN BR.
CHOLISTAN DESERT
RAHIM YAR KHAN
INDUS
BALUCHISTAN PROVINCE
SIND PROVINCE
INDIA
N
LEGEND
International Boundary (B)
Provincial B
River
Canals/Links (L)
Cities
Dams/Reservoir
Barrage/Head works
Syphon
Motorway M-2
Reclamation Farm
M. Azhar Javaid
Land Reclamation Directorate
Lahore.

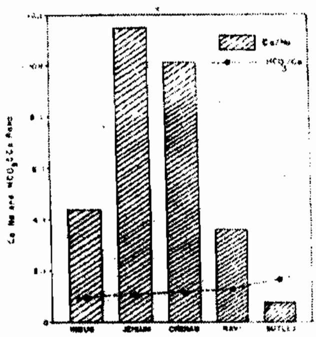


Figure 2 The Ca/Na and HCO_3/Ca ratio in river waters of Punjab

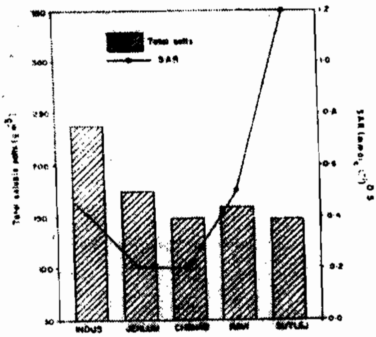
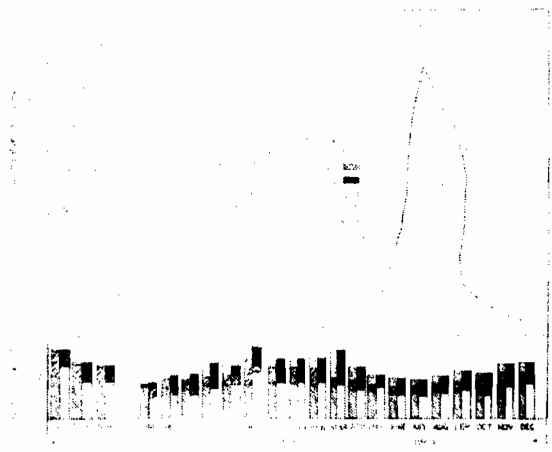


Figure 3 Total soluble salts and SAR values of river waters in Punjab.



[illegible] Indus River at Darband

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