Impact of Floods on Groundwater—A Case Study of Chaj Doab in Indus Basin of Pakistan

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Abstract

Groundwater is the most valuable natural resource and playing globally a vital role in agri-based economy of the nations. Uncertainty and scarcity of surface water, tremendous increase in population, and urbanization have shifted the pressure towards the groundwater. Pakistan has become 4th largest user of groundwater after India, USA and China. Groundwater has helped in increasing cropping intensity from 67% in 1947 to 150% or even more in some irrigated areas in Indus River Basin (IRB) of Pakistan at present. In Punjab province, more than one million private tubewells are extracting groundwater to meet about 40-50% crop water requirements. On the other hands, devastating floods cause huge damage to the agricultural production, physical infrastructures and human lives. Very less research has been done on the impacts of floods on aquifer recharge. To evaluate the impacts of flood 2014 on aquifer storage a quantitative analysis of groundwater levels data from about 200 piezometers has been carried in Chaj Doab (area between two rivers—Chenab and Jhelum) in Indus River Basin (IRB) of Pakistan. Results have indicated that groundwater levels in Chaj Doab are rising at an average annual rate of 0.4 ft. It has been found that during 2014 maximum area (44%) lies under depth to watertable range of 5-10 ft. It has been observed that flood 2014 recharged 1.319 MAF of water to groundwater reservoir. Over-exploitation, deterioration of quality of groundwater, secondary salinization, lack of regulatory framework, scarcity and uncertainty of surface water, lack of education and awareness among the stakeholders, gaps in monitoring and mapping of aquifer extent, lack of coordination and institutional setup have been identified as potential challenges for groundwater management in the study area. Flood water contributes significantly to aquifer recharge and the depleted aquifer can act as a storage for flood water to lessen the flood-intensity.

Keywords

Groundwater, recharge, storage, aquifer, Punjab, Chajdoab, Pakistan

1. Introduction

Climate in Pakistan is semi-arid, and economy of the country is agriculture-based. Water resources comprise rainfall, glaciers, and groundwater. These resources are not only finite but are under tremendous pressure and are exhaustible [1]. Agriculture in the country is dependent on waters of Indus River and its tributaries, where 100% of cash and 90% of food crops depend on irrigation. Presently, water scarcity conditions are prevailing in the country [2]. Agriculture is the single largest sector of Pakistan's economy contributing about 22% of the Gross Domestic Product (GDP), is the source of earning of 45% of the total employed manpower and brings it as 8th largest food producing country where irrigated agriculture contributes over 90% of food production of the country [3]. Agriculture underpins the food security and re-

duces poverty [4, 5] and is central to economic growth in Punjab province [6]. However, the potential of agricultural production and to bring more area under cultivation depends on availability of water. Whereas water is not evenly distributed over the year and seasonal variation, droughts and floods can create extreme situations [7, 1]. At present in Pakistan, about 1.2 million tubewells are extracting about 60 BCM [8, 9] and Pakistan has become the 4th largest user of groundwater in the world [10]. Groundwater in Punjab has increased due to increasing irrigation demands led by increased cropping intensity [11], growing population, and fragmentation of farm sizes, and stagnant irrigation supplies [1, 6, 12]. Groundwater is playing vital role by underpinning food-security and livelihood of rural communities in Punjab and contributes about 40%-50% of irrigation water requirements [13]. Climate related disasters like floods and droughts are also very common in Pakistan; for example, during flood 2010, one fifth of total land of the country was submerged [5]. Flood water can contribute to groundwater significantly; for example [14] have reported that 57%-61% of total recharge to groundwater occurred from floodwater spreading in Iran. They further narrated that floodwater is a vital resource for improving crop yields and aquifer storage. G. Z. Hassan and F. R. Hassan [15] found that flood water is a source of groundwater recharge. Chinnasamy, et al. [16] while working in India found that managed aquifer recharge practices by spreading the flood water can reduce the negative impacts of floods and can replenish the depleted aquifers. Under the present study, groundwater levels data have been analyzed to evaluate the impact of flood water on groundwater storage and rising of water levels in the aquifer.

2. Description of Study Area

2.1 Location and geography

This study has been carried out in Chaj Doab (“doab”, a local term means land between two rivers and Chaj represents two rivers Chenab and Jhelum) which lies between longitudes $72^{\circ} 20'E$ to $73^{\circ} 30'E$ and latitude $31^{\circ} 60'$ to $32^{\circ} 60'$. The Chaj Doab covers an area of about 10,000 km² which is bounded by Chenab River on the south-east and Jhelum river on the north-west in Punjab province of Pakistan. This area is leading in citrus production and other crops playing paramount role in economy of the country. It comprises the districts of Sargodha (56%), Mandi Bah-ul-Din (26%), Jhang (14%) and Gujrat (4%). Upper Chaj Doab is the north central part of the Punjab plains and lies on the north eastern rim of this basin where it joins Himalayan foothill zone. It covers a vast canal network up to distributaries and minors. The mean annual rainfall is 426 mm and mean annual temperature is $24^{\circ}C$ with the mean maximum of $31^{\circ}C$ and mean annual minimum of $18^{\circ}C$. The Monsoon rainfalls are dominant and contribute major part towards annual precipitation. The irrigation system mainly consists of Lower Jhelum Canal (LJC) and Upper Jhelum Canal (UJC) in the southwest and northeast respectively. Major features and location of study area are shown in Figure 1. The slope of the land in most of the Punjab is towards southwest and ranges from about 2 feet per mile in the northern part of the area to less than 1 foot per mile at the southern end. In the center of the doab, terraces or bars rise as much as 50 feet above the level of the adjacent flood plains. The low relief of the plains and terraces is broken by a few scattered bedrock hills in Chaj Doab.

Figure 1. Location of study area-Chaj Doab showing main features.

2.2 Climate and hydrology

The climate of the Punjab, typical of the low-lying interior of the Indo-Pakistan subcontinent, is characterized by large seasonal fluctuations in temperature and rainfall. It is continental, ranging from semi humid in the northeast to arid in the southwest. Rainfall is generally scant and sporadic and, therefore, not a dependable source of crop moisture. Annual precipitation at different locations varies considerably over the year. The precipitation ranges from 60 mm to more than 75 mm per year in the upper reaches of Chaj Doab [17, 18]. Precipitation diminishes to the southwest; the lower half of Chaj Doab receives less than 36 mm of rain per year. Mean Monthly Rainfall (mm) and Temperature ($^{\circ}\text{F}$) for the period 2002-2013 at Sargodha Station in Chaj Doab is shown in Figure 2. Spatial and historical pattern of mean annual precipitation obtained from different rain gauging stations located within the Chaj Doab for the periods 1916 to 1957 is shown in Figure 3, which indicates that rainfall decreases from North-East to South-West direction.

Figure 2. Average monthly rainfall (mm) and temperature ($^{\circ}\text{F}$) at Sargodha station in Chaj Doab [18].

Figure 3. Isoheytal map of the Chaj Doab showing average annual precipitation (data source: [18] & [19]).

In addition to rainfall, canal water is also available for irrigation purposes from the Chenab and Jhelum rivers. The flows of the Chenab and Jhelum rivers are regulated at four major headworks to ensure adequate irrigation supplies to the Chaj Doab area and other areas of the Indus Basin. Both rivers meet at Trimmu Barrage Irrigation network in Chaj

Doab is shown in Figure 1.

2.3 Soils Stratification

The soils of the Punjab are composed of alluvial material which was carried out from the Himalayan ranges by tributaries of the mighty Indus River system. Frequent changes in the rate of flow of the streams, recurrent floods, and ponding of the sediment-laden waters have created a varied and mixed soil pattern throughout the area. Although the magnitude of reworking of the alluvium by wind action cannot be ascertained everywhere, it is generally believed that the soils in much of the area have been modified by deflation and redeposition [20]. Moreover, extensive areas of sand dunes are found in the central desert of Thal Doab, and, locally, in the lower reaches of the other doab. Generally, the soils cannot be classified by genetic characteristics, and therefore they have been grouped into five basic series according to subsoil texture. Semi detailed soil surveys have been completed in most of the area. Detailed descriptions of the soils in Chaj Doab have been reported by [21] and [22]. In many respects, the soils show a high degree of similarity throughout the area. These are reddish-brown to greyish brown, mostly moderately coarse and medium-textured soils, containing high percentages of fine to very fine sand and silt. The clay part consists largely of non-swelling minerals, which may account for favourable permeability and characteristics of the soils. The soils of the area, in general, are intrinsically fertile and have high potential productivity. In many areas, however, organic matter and plant nutrients, such as nitrogen and phosphorus, have been greatly depleted. When adequate water supply and the requisite manures or chemical fertilizers are provided, the soils of the Punjab normally attain a high level of productivity. Preliminary land-classification data for Chaj Doab indicated that 55-60 percent of the area was unsuitable for irrigated farming in 1962, mainly as the result of waterlogging and salinity. Reclamation measures can rehabilitate most of these lands. If the salinity were eliminated, more than 90 percent of the lands would be classified as suitable for farming [20]. With the help of ERS technique, freshwater layers could be targeted for drilling a well up to the lower end of these layers to avoid unnecessary drilling. The thicknesses of these layers also guide us for well site selection at a point, which has bigger thickness within the land holding of the farmers. This technique is a non-destructive and useful method to detect depth and thickness of various subsurface geological formations and the groundwater quality within these formations of the layers Comparison of bore logs in Chaj Doab using electrical resistivity survey (ERS) is shown in Figure 4 [23].

Figure 4. Comparison of bore log analysis with ERS result.

2.4 Hydrogeology of Chaj Doab

During the year 1954 and 1963, forty-four pumping tests were conducted in Chaj Doab by the Groundwater Development Organization (GDO) and its successor, the Water and Soils Investigation Division (WASID). The depths of the wells were observed in range from 135 feet to 300 feet. Thickness of the aquifer is generally greater than 1,000 feet. All test wells were screened in the unconsolidated alluvial deposits. The average permeability of 36 tests in Chaj Doab was found out to be 0.0028 cfs/ft² and about 69 percent of the results were in the range from 0.0014 to 0.0046 cfs/ft² [18, 19].

Locations where aquifer tests conducted in Chaj Doab are shown in Figure 5. Average permeability/specific yield at various locations in Chaj Doab is given in Table 1.

Figure 5. Location of aquifer test site in Chaj Doab (derived from data source [18] & [24]).

During year 2008-09, Irrigation Research Institute also conducted preliminary survey and drilled sixty exploratory boreholes in the field at various critical sites in Punjab to explore aquifer characteristic and soil stratification for identifying the potential site for artificial recharge of aquifer. Soil samples from all these sixty sites were collected and analyzed for determination of lithology and grain size distribution [25]. These investigations support the previous findings.

3. Material and Method

3.1 Groundwater levels and behavior

As reported by [20, 24] and many other sources, the water table during pre-irrigation period was very deep especially in the centres of doabs and the ground-water hydraulic system was in a state of dynamic equilibrium. Under the natural environment, any system tends to adjust itself in equilibrium conditions. After inception of canal irrigation network in the Subcontinent by the British, the water table started rising due to recharge from canals and irrigation fields [26]. A rise of groundwater levels in Chaj Doab has been observed in the range of 50-70 ft over the period from 1900 to 1960 [19]. During the period 1960-70s, water table became very shallow causing dual menace of waterlogging and salinity in many areas of Punjab [26-29]. Contour-map of depth to watertable in Chaj Doab during the 1960-70s is shown in Figure 6, which indicates that watertable was at the depth of 6 ft (upper part of Chaj Doab) and about 12 feet in the lower

reaches near confluence point at Trimmu.

Table 1. Average permeability/specific yield at various locations in Chaj Doab [18, 19]

Sr. No.	Aquifer Test Sites	Site	Average Permeability cfs/ft ²	Specific Yield	DTWT (ft)
1.	3	R.D.5400 Sulki Br	0.0029	0.08	8
2.	4	Ghazni Disty	0.0023	0.39	4
3.	5	Lower Jhelum Canal	0.0024	0.08	7
4.	6	R.D. 41000, Southern Br	0.0029	-	5
5.	7	R.D. 2700 Lower Jhelum Canal	0.0036	0.08	9
6.	9	R.D. 10000 Khadir Br	0.0040	-	12
7.	10	Alipur Noon	0.0036	-	3
8.	11	Melowal Village	0.004	-	15
9.	14	Kot Moman Village	0.0036	0.05	9.1
10.	16	Rakh Bohiwal	0.0033	-	7
11.	17	Bhairowal	0.0045	0.22	8
12.	20	Kot Khan	0.0019	0.21	9
13.	21	Chilianwala	0.0018	0.13	5
14.	22	Dharema	0.0031	0.18	7
15.	23	Wazir Kot	0.0022	0.2	14
16.	24	Kot Moman	0.0021	0.18	5
17.	25	Laluwali	0.0014	0.25	6
18.	26	Mitha Lak	0.0026	0.14	9
19.	27	Ghauswala	0.0032	0.17	9
20.	28	Choranwala	0.0015	0.04	3
21.	29	Chak Saidu Phalia	0.0033	0.1	7
22.	30	Sahiwal	0.0021	0.12	6
23.	31	Tail Sobi	0.0029	0.36	13
24.	32	Jhanian Shah	0.0030	0.02	4
25.	33	Machu Khadi R.D. 19-20	0.0024	0.14	6
26.	34	Manghat	0.0032	0.1	15
27.	35	Shah Jiwana	0.0016	-	9
28.	36	Tail Nurewala Disty	0.0046	0.12	7
29.	37	Taalib Wala	0.0046	0.29	10
30.	38	Hassan Khan	0.0025	-	9
31.	39	Kishangarh	0.0029	0.16	10
32.	40	R. D. 170 Shahpur Br	0.0019	0.2	5
33.	41	Takht Hazara	0.0038	0.17	13
34.	42	Bhalwal	0.0025	0.08	4
35.	43	Chak 27 Fagirian	0.0024	-	5
36.	44	Gujrat	0.0021	0.08	7

Punjab Irrigation Department (PID) has installed a network of about 3,000 observation wells in the canal commands of the province. Groundwater levels are being observed twice i.e., pre and post monsoon during a year. Location of installed piezometers in study area (Chaj Doab) is shown in Figure 7. Data from these points for the period 2011 to 2016-covering the flood 2014 event have been analyzed and plotted for different investigations and evaluations.

Data of depth to water table for the study period 2011-2016 have been plotted to prepare the maps using ArcGIS software which are shown in Figures 8 and 9.

Figure 7. Depth to water table for Chaj doab pre and post monsoon 2011 [15].

Figure 8. Depth to water table (feet) map of Chaj Doab for pre and post monsoon 2016.

Percentage of areas under different ranges of depth to water table for the study period (2011-2016) are tabulated in Table 2. Trends of data for the years 2011, 2014 and 2016 are shown in Figure 10.

Table 2. Temporal trend of area under different depth to water table ranges

Year/season	Depth to water table ranges (ft)	Area under different ranges of depth to water table (km ²)						
		0-5	5-10	10-15	15-20	20-25	25-30	> 30
Pre-2011	Area (km ²)	220.82	2,826.48	3,010.12	1,810.01	1,037.02	1,037.02	95.20
	%age of area	2	28	30	18	10	10	0.95
Post-2011	Area (km ²)	732.79	3,150.13	2,627.77	1,796.61	818.16	300.91	30.93
	%age of area	8	33	28	19	9	3	0.33
Pre-2014	Area (km ²)	247	3,310	3,212	1,719	931	444	22
	%age of area	2	33	32	17	9	4	0.22
Post-2014	Area (km ²)	1528	4,392	1,865	1,115	728	251	3.00
	%age of area	15	44	19	11	7	3	0.03
Pre-2016	Area (km ²)	626.97	4,078.45	2,772.01	1,388.09	791.03	206.7	4.63
	%age of area	6	41	28	14	8	2	0.05
Post-2016	Area (km ²)	976.80	4,467.12	2,288.87	1,218.47	715.23	90.89	2.34
	%age of area	10	46	23	12	7	1	0.02

Figure 9. Area (%) under different ranges of depth to water table in Chaj Doab.

The area under depth to watertable more than 30 feet was 95 Km² in pre-monsoon 2011 which decreased to 30 Km² in post-monsoon 2011 and it further decreased to 2.65 Km² in post-monsoon 2015 in Chaj Doab area.

3.2 Flood 2014 and groundwater recharge

Canals, rivers, and floods are major sources of recharge in addition to rainfall. Flood 2014 was a major flood which caused recharge of aquifer in Indus Basin including the Chaj doab. Different research and field investigation studies have been carried out by Irrigation Research Institute (IRI) from time to time to evaluate the seepage losses recharging the aquifer under lying the Indus Basin in Pakistan. Under a JICA funded study, 24 seepage tests were conducted on 21 channels (distributaries and minors) in Lower Jhelum canal (LJC) system in Chaj doab. The seepage rates calculated by inflow outflow method on the specified locations were in the range from 1.183 to 13.293 cubic feet per second per million square feet (cfs/msf) [30]. Later, 37 seepage tests were performed using ponding method on 25 channels in the saline zone of Lower Jhelum canal (LJC) circle in Chaj doab; seepage rates calculated were in the range from 0.669 to 6.874 cfs/msf [31]. After flood 2014, a study was conducted by IRI to estimate the impact of flood water on groundwater recharge which found that floodwater contributes significantly towards recharging the aquifer. Observed data on depth to watertable from about 200 piezometers in Chaj Doab were analyzed, plotted and changes in aquifer storage were calculated for the study period. Groundwater recharge is a major component of any water balance study of a hydrologic system; but is almost impossible to be measured directly in the field. It is always estimated, for which a number of methods are available [32] and [33]. Under present study the directly observed data on groundwater levels has been used to estimate the gross recharge to the aquifer using specific yield method. Chaj Doab was divided into 20 polygons (Thiessen Polygons using ArcGIS) as shown in Figure 11. Each polygon was represented by a piezometer. Depth to watertable (DTWT) data (pre and post monsoon seasons) have been plotted and maps are shown in Figure 12. Difference of depth to watertable during pre and post monsoon seasons has been plotted in Figure 13. Rise/fall in each polygon was calculated and recharge (change in aquifer storage) has been estimated by specific yield method by following equation [15]: -

$$GWR = \sum_{i=1}^n (R_i * A_i * S_y i)$$

Where GWR is groundwater recharge, n is number of polygons, R is rise/fall in groundwater level in ith polygon, A is area of polygon, S_y is the specific yield.

Figure 10. Study area divided into 20 polygons.

Figure 11. Depth to water table for Chaj Doab pre and post monsoon 2014 [18].

Figure 12. Difference between depth to water table in Chaj Doab during pre- and post-monsoon 2014 [18].

4. Results and discussions

Statistical and geo-spatial analysis of data have revealed that groundwater levels in Rechna Doab are rising and there is significantly increase in aquifer storage on annual basis especially during the flood season of 2014. Groundwater levels at selected points (in each polygon) have been analyzed for pre and post flood 2014, to see the impact of flood water on groundwater level fluctuations. Watertable rise/fall at different locations during flood 2014 has been depicted in Figure 14. The results have revealed that average rise in watertable during pre and post monsoon period of 2014 is 2.3 ft. Generally, in the upper part of the study areas which falls in head reaches of the canals system (polygons 1-10), water table rise is more as compared to the polygons in the tails reaches (11-20). This trend can be attributed to more availability of surface (canal) water in head reaches- resulting less extraction of groundwater and vice versa in the tail reaches. Summary of statistical parameters of depth to watertable data is given Table 3. This table indicates that depth to water table is decreasing as we move from 2011 to 2016, which indicates rising trends of groundwater table in the study area. Maximum DTWT decreased from 34.3 ft (post-11) to 31.2 ft (post-16) over the period of 5 years, which indicates about 0.62 ft year rise in water table. However, rise in watertable during the year 2014 (flood year) is 2.3 ft.

Figure 13. Average water level raise (ft) at different locations in Chaj during flood 2014.

Table 3. Statistics of depth to water table below natural land surface (ft) from 2011-2016

Parameters	Time (Pre= pre-monsoon and Post = Post-monsoon)											
	Pre 2011	Post 2011	Pre 2012	Post 2012	Pre 2013	Post 2013	Pre 2014	Post 2014	Pre 2015	Post 2015	Pre 2016	Post 2016
Max	36.6	34.3	35.0	32.3	32.5	31.9	32.3	30.7	31.8	31.3	31.4	31.2
Min	4.2	3.3	4.6	3.1	3.3	3.1	3.3	3.1	3.4	3.2	3.3	3.1
Mean	14.8	13.4	14.5	13.3	13.7	12.8	13.5	11.2	11.9	11.0	11.9	11.2
STD	9	9	8	8	8	8	8	8	8	8	8	8

Maximum and water table rise in all polygons in the study area for the years 2011, 2014 and 2016 have been shown in Figure 15. It indicates that the rise in water table during 2014 is higher than those calculated for 2011 and 2016, which indicates the significant contribution of flood water to the aquifer storage. Similarly, change in aquifer storage for three years has been calculated using specific yield method comes out to 0.836, 1.319 and 0.390 million-acre-feet (MAF) for the years 2011, 2014 and 2016 respectively as shown in Figure 16. Again, it is evident that recharge to the aquifer during 2014 is much higher as compared with 2011 and 2016 values. This indicates that floods are significant source of aquifer recharge. Trends of depth to water table in study area for 2011 and 2016 have been plotted in Figure 17. This indicates the rising trends of groundwater levels over the period of 5 years. It further indicates that gradient of groundwater flow is from upper part of the doab to lower part.

Figure 14. Water level rise (ft) in Chaj Doab showing the impact of flood 2014.

Figure 15. Change in aquifer storage (MAF) in Chaj Doab.

Figure 17. Depth to water table trends in study area for 2011 and 2016.

5. Conclusion and Recommendations

5.1 Conclusions

It has been found that during flood 2014, average water table rise is 2.3 ft. Total recharge of aquifer (change is storage) during flood season 2014 in Chaj Doab has been estimated as 1.319 million-acre feet (MAF) using specific yield method. Groundwater is one resource and there are many users like industries, agriculture, domestic, livestock, wildlife, parks, and energy production etc. Potential identified threats to groundwater reservoir are uncontrolled and un-planned over-pumping in freshwater areas due to increasing demands of food and fibre, untreated effluents (domestic, industrial, agricultural), lack of recharge of aquifer (natural as well as artificial) and population increase is major driver of these challenges. Groundwater showed nearly constant rise of 1.7 to 2.2 feet per year. As the groundwater approached nears 20 feet, the rise per year started to slow down. It was noted that the rise from 10 to 20 feet continued to decline considerably. Its average rise per year became about 0.5 feet upward of ten feet either stopped or increased by about 0.1 feet per year till it reached within five feet. During years 2011-2015, water levels in the Chaj Doab rose from 0.3 to 2.6 ft per year with average 0.9 ft. Generally, in brackish zones groundwater level is in rising trend and is causing waterlogging and salinity. Total recharge of aquifer during flood season 2014 in Chaj Doab was 1.319 MAF, which indicates that there is flood contributed significantly towards recharging the aquifer. Average rise in Chaj Doab during flood 2014 was 0.77 ft. There is a lack of communication/coordination among different Government Departments/agencies and the various stakeholders/consumers, managers, and NGOs, etc. Reduced pumpage from the areas of poor groundwater quality and continuous use of saline groundwater for irrigation will cause secondary salinity and will affect adversely the crop productivity.

5.2 Recommendations

Detailed program of groundwater monitoring to prepare groundwater potential maps for further hydro-geological investigations is direly needed. 1) A combination of incentives, including more stringent regulation, enforcement and well-targeted subsidies, can help to reduce deterioration of groundwater reservoir. 2) options, like removing subsidies for water-intensive crops, charging for electricity, creating a permit system for new wells and power connections, artificially re-charging aquifers with rainwater, community monitoring of aquifer levels, and subsidizing drip irrigation are required to be opted for groundwater management. 3) institutional and holistic regulatory framework for groundwater monitoring and management needs to strengthen and upgraded on modern lines. 4) strict enforcement of existing regulations till formulation of new ones. 5) awareness raising and capacity building campaigns for all stakeholders. 6) Development of IWRM framework and its implementation. 7) measures to combat dual menace of waterlogging and salinity need to be implemented.

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