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Spatio-temporal investigation of groundwater quality variation employing nested piezometers downstream of Kotri Barrage toward the Indus Delta

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ABSTRACT

The Indus Delta is an endangered wetland on the Ramsar list due to a continued decrease of river flow toward the delta, resulting in seawater intrusion into the inland areas and deteriorating the potable patches of shallow groundwater and wetland areas. The groundwater in the lower Indus Basin is brackish, except for a few potable pockets, which are shrinking due to water extraction for drinking purposes. The gap thus occupied by saline water permanently degrades the potable groundwater. This paper correlates the potable patches with surface seepage due to either rainfall or river flows, to recommend a continuous flow of fresh water in the river system, and a revival of the ruined wetlands and lagoons. Twelve nested piezometers at various depths have been installed in the study area to monitor the groundwater quality temporally transformation. The water samples have been periodically collected to analyze physical and chemical properties for three years. The data trend indicates the rapid changes in shallow groundwater quality (up to the depth of 10 m) to the surface availability of freshwater. An area of 378 km^2 was turned from saline to fresh groundwater with only two spells of rainfall. The result confirms the positive impact on groundwater quality improvement due to rainfall and water in river tributaries. Based on this analysis, it is recommended to replenish the lagoons and shallow lakes with fresh water. Canals should run continuously to constantly recharge the shallow groundwater as the only source of drinking water in the study area.

Keywords: Nested piezometer; Groundwater deterioration; Seepage; The Indus Delta

1. Introduction

German-watch, an independent climate change observer, rates Pakistan as the 7th most affected country by climate change from 1997 to 2016 and indicates Sindh province as the worst affected by extreme weather events, especially hydrological hazards [1]. Pakistan, being an agricultural country, is heavily dependent on the flow of the Indus River, which is one of the largest rivers in Asia and the 12th largest in the world. The Indus River originates in the Tibetan Plateau (China), crosses Kashmir (Indian part) and enters into Pakistan, crossing the full length of Pakistan and flows into the Arabian Sea. At its terminus, it forms the Indus Delta [2].

The Indus Delta is the 5th largest delta in the world, covering an area of 41,440 km^2 [3,4] with the 7th largest unique species of mangrove forests (*Avicennia marina*) of the arid climate. That forest provides a nesting place for hundreds of species of migratory birds [5]. The post-1960s development in the water sector in Pakistan, the construction of new dams and water structures to increase the agricultural

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land production to feed the growing population [6], which reduced the river flows to the delta, resulting in the creeping death of the delta ecosystem and habitat. The associated impacts of climate change resulting in erratic rainfall and increasing periods of drought reduced the freshwater availability in the study area.

The decreasing river flows resulted in seawater intrusion, which degraded the land and the limited potable water patches in the region. The land and water deterioration significantly impacted the human population, migratory birds, and the mangrove forest, which provides the ecosystem for hundreds of species of shrimp and fish [7,8]. This desolation of the Indus Delta provoked the international environmental community. As a result, the Indus Delta and its associated ecosystem and wetlands were included in the list of Ramsar protected sites [9]. The international stress resulted in legislation for the allocation of 10 MAF river flows to improve the environmental sustainability of the Indus Delta [10]. This flow was barely achieved and only in the flooding season for merely a few days/weeks; the remainder of the time the river has no flow of water that reaches the delta [11]. The flood recurrence has a time interval of 8 to 10 years in the region.

Before the increase in dams, the Indus Delta had fertile land, producing red rice in abundance, and Keti Bander (KB) (a small coastal town in the Indus Delta region) was a busy seaport and trading area [12]. The literature review reveals that similar issues have affected other delta areas, as well. However, the devastation rate of Indus Delta is more rapid, compared to other deltas in the world [13]. Research confirmed a drastic decline in agricultural land from 116,928 acres to 48,787 acres in 20 years from 1998 to 2018 [14]. The revival of wetlands and lagoons in the region and recharge of groundwater with potable water is a localized solution to stabilize the deteriorating situation of Indus Delta. Groundwater recharge is a sustainable alternative and a natural solution to retain potable groundwater indicated by various researchers [15–20]. The results of a few of the related studies are discussed below.

Dimri et al. [21] conducted their research on climate change impacts on the reduction in water budget for the Indus River basin (IRB) and confirms the vulnerability of the IRB while confirming the control of the upper IRB to the lower IRB for the availability of water. The impact of the reduction of freshwater and sediment discharge in the Indus deltaic region was that the wellbeing of the Indus Delta demands a minimum continuous quantity of freshwater and sediments be discharged to the delta on a year-round basis [2]. Similar research was conducted on Indus Delta degradation and concluded the need to release an established minimum of fresh water to sustain the delta, along with other measures to construct environmental-friendly protection works [12].

Dorau et al. [18] conducted a time series analysis on wetland restoration through re-wetting practices to sustain the mesotrophic fen in northern Germany against the impact of climate change. That research showed some contradiction with wetland management and re-wetting methods; however, the study confirmed the adaptation of re-wetting methods in certain ways with prior validation. Another related study on shallow aquifer recharge from irrigation in a semiarid region in New Mexico, USA confirmed that the water table responded seasonally due to canal seepage and percolation from the irrigated areas, while flooding practices using irrigation impact more in alluvium soils [22].

The variability in groundwater quality and pollutant concentration levels in the northwest of Iran has been determined, employing geographic information system (GIS) kriging tools and chemical analysis of water samples. The results indicated the trend of decreasing groundwater level with increasing concentration of salinity in some portions, measured over a decade. The research successfully identified the affected areas and suggested measures to implement that would improve the management of groundwater [23].

Pham and Lee [24] assessed seawater intrusion and groundwater extraction in the coastal belt of the Red River Delta, Vietnam. They engaged the SEAWAT model to predict the seawater intrusion potential with respect to sea-level rise, extraction of groundwater, and seasonal recharge of groundwater. The results revealed that due to the uncertainties of transport parameters, the seawater intrusion potential was significantly affected.

Investigating the spatiotemporal variation of the groundwater table, employing GIS techniques and incorporating the available groundwater data with WASA library, Abbas et al. [25] adopting a kriging tool in ArcMap, prepared layered maps of water table fluctuation in various periods. The results of their research revealed that the potential recharge zones have a stable water table. They recommended introducing an artificial means of recharging groundwater. Wolthek et al. [26] introduced the practice of deep-well injection in the Netherlands to desalinate the brackish groundwater by installing reverse osmosis equipment. They injected the high-concentrate saline water into the deep aquifers and maintained the buffer zone of the fresh-brackish interface.

While studying the challenges and prospects of sustainable management of the Indus Basin groundwater in Pakistan, Qureshi et al. [27] emphasized the multi-sectoral approaches including wastewater reuse, policy reforms, and on the artificial recharge of the aquifers. They confirmed that the groundwater recharge source through seepage from earthen canals and emphasized the necessity to regulate the controlled withdrawal of groundwater. The improvement in groundwater quality due to the entry of freshwater was monitored in Potharlanka Island in the Krishna Delta of India. The research confirmed a 10% increase in fresh groundwater after activation of recharging wells and heavy rainfall flooding in the area [28]. Mitsch and Day [29], research on the restoration of wetlands in the Mississippi-Ohio-Missouri River Basin, concluded that there was a need to adopt multi-sectoral approaches and emphasized the need to conduct further contextual research on reducing the uncertainties.

Based on the above findings, a localized solution to the gradual land degradation and groundwater quality deterioration in the study area has been proposed. The river water allocation for environmental sustainability of the study area has long been an unresolved issue; this has triggered conflict in the region. None of the past research proposed an alternate solution to retain the shallow groundwater utilizing rain harvesting in this region, nor any research has been conducted so far on different groundwater layers. The current study will provide a rational basis for the recommendation of groundwater recharge practices along with the revival of surface water bodies, including wetlands, lagoons, and water conveyance structures that can divert heavy rainfalls.

2. Study area

The study area developed as an alluvial valley formed by the large sediment load from the Indus River flowing along approximately the same path for millions of years [30]. The study area can be described by and be divided into two geological features, the flat plains, with an average gradient of 1 m/1 km, and the rocky area, with a maximum elevation of 300 m. The study area constitutes the jurisdiction of Thatta District on the right-hand side, and Sujawal District on the left-hand side of the Indus River, downstream from the Kotri Barrage towards the Arabian Sea, including the Indus Delta. Geographically, the area is located at latitude 24.00–25.15 and longitude 67.00–68.15 (Fig. 1). The arid coastal area has an average annual rainfall of 200–250 mm [31]. This area is a unique distinction of mangrove arid species and is a nesting place for millions of migratory Siberian birds. The area has been listed as a Ramsar protected site, due to the drastic reduction in river flows and the resulting in rapid degradation of the delta and coastal habitat.

3. Method of analysis

The study area was surveyed physically to demarcate the locations for installation of experimental setup of nested piezometers in appropriate places and the locations with a potential difference in groundwater quality. The piezometers locations was selected on both sides of the Indus River in the study area and along the coast of both districts. After the installation of nested piezometers, the periodic water samples have been collected through standardized methods [32–36] from depths of 10, 14, 18, 22, and 26 m. The depth of the piezometers were selected based on bore-log data. A specially designed and fabricated manual water pump was employed to collect the water samples from the specific depths, simultaneously (Fig. 2). Physical and chemical analysis was conducted on the water samples collected after hydrological events, such as rainfall or drought spells for two years. The analysis of electrical conductivity (EC), potential hydrogen (pH), turbidity, total dissolved solids (TDS), carbonate, bicarbonate, calcium, magnesium, and nitrate tests have been conducted using standard lab equipment and methods [37]; however, in this paper, only EC values have been plotted. The results were developed using the ArcGIS 10.5 interpolation method employing a Kriging tool due to its suitability for an irregular distance of data locations, high accuracy and low bias [38].

The periodic water samples were collected in autoclaved air-tight jars to avoid contamination. The EC of water samples were also checked on the spot using HANNAN H1991300 (portable EC, pH and TDS meter). The water samples were brought to U.S.-Pakistan Centers for Advanced Studies in Water soil and water testing lab for analysis of above-mentioned parameters. The temporal and depth-wise results of water quality were matched with rainfall data to observe the correlation between them.

4. Results and discussion

The water samples were collected from 5 depth layers of 12 nested piezometers in March 2017, July 2017, November 2017, March 2018, July 2018 and the last samples were

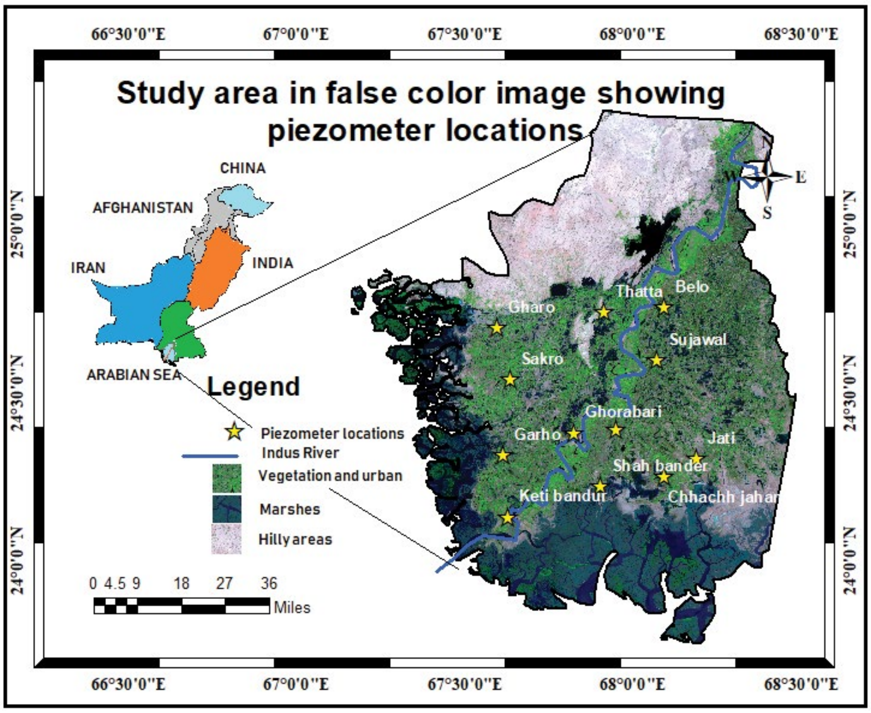


Fig. 1. Study area imagery in false color showing piezometer locations.

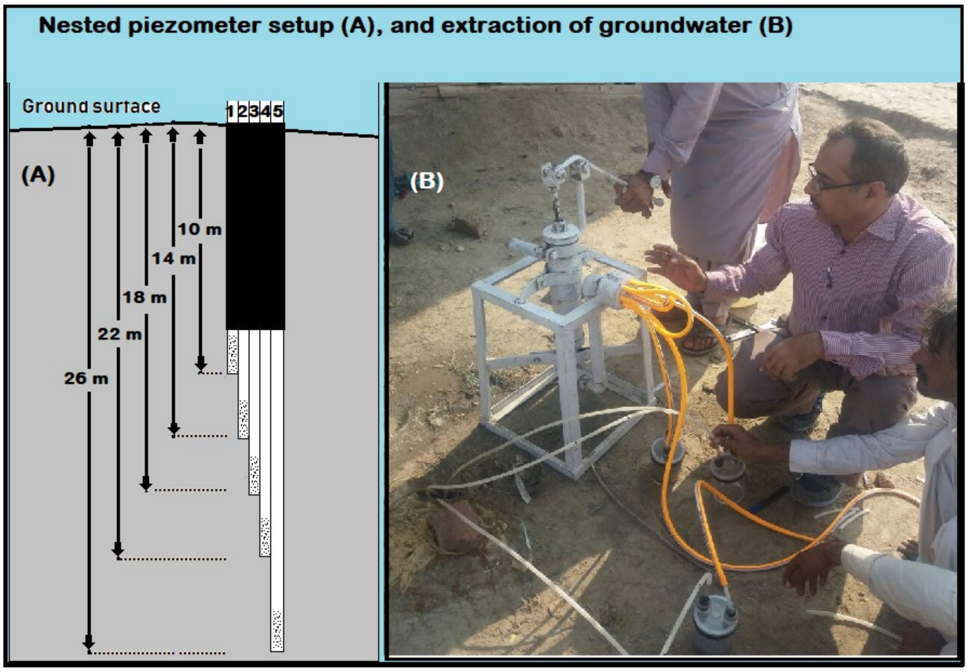


Fig. 2. Nested piezometer setup and extraction of groundwater from the nested piezometer.

collected in January 2019. The rainfall during this period was recorded consequently low as compared to the average annual rainfall for this region. Table 1 represents the EC values at groundwater depths/layers of 10, 14, 18, 22, and 26 m from the ground surface with respect to rainfall impact. It is observed that the only groundwater quality improvement was seen in the first 10 m layer. The other samples, at deeper depths, showed no variation with time and limited rainfall. The figure also demonstrates the trend of high salinity in the coastal belt; the remainder of the area has lower salinity.

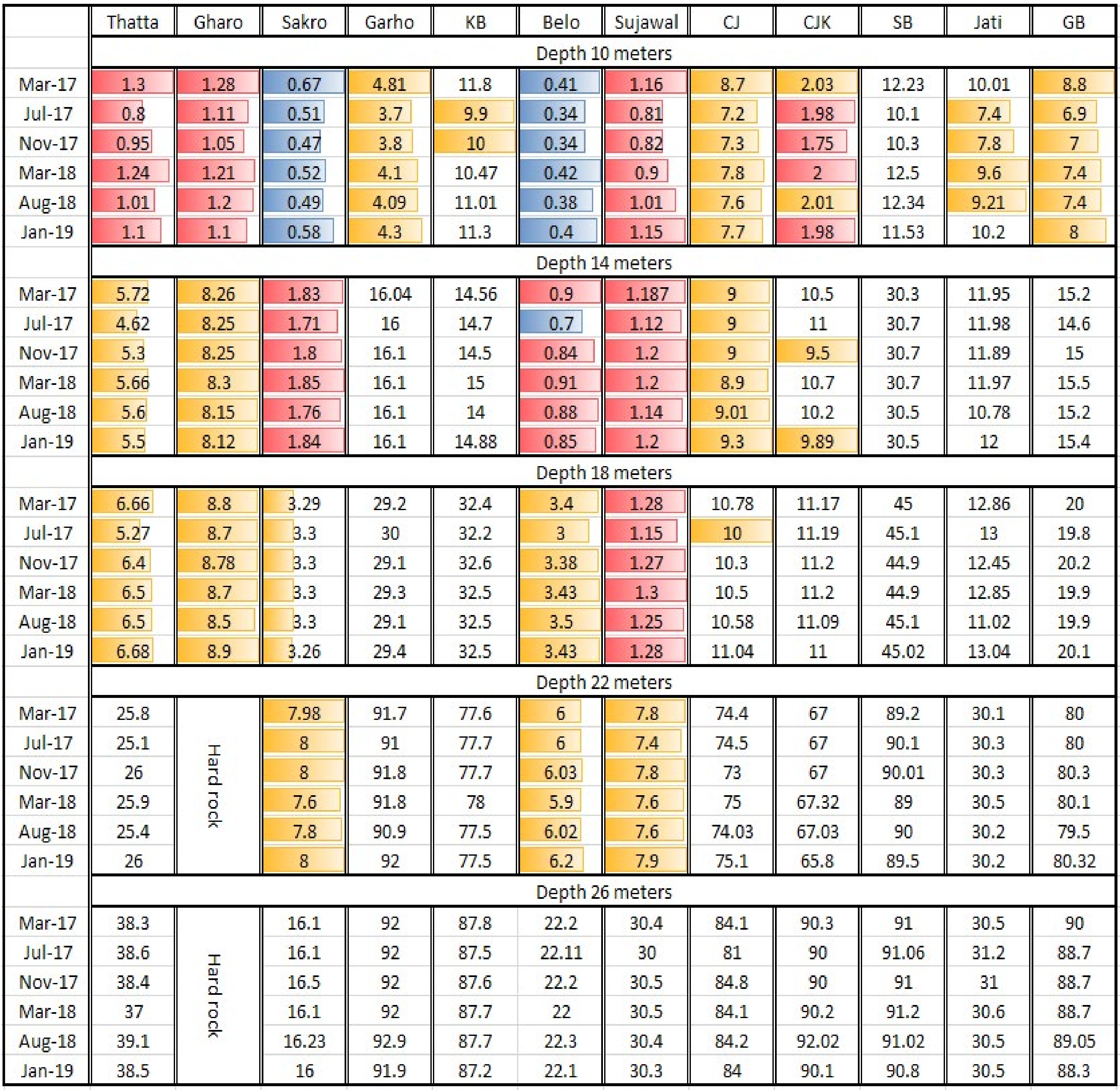
The positive impact of flood spreading through infiltration ponds was recorded by Ghazavi et al. [39] in arid and semi-arid regions. The authors concluded that remarkable improvement in groundwater quality and water table level was recorded. The similar results were drawn by Mondal [28] and conclude that 57% of the study area was under seawater intrusion while after flooding, the seawater intrusion area was reduced to 38%. The results of the current study are in synergy with the work of other researchers [9,16].

The temporal and spatial variation in groundwater EC level demonstrates a clear picture of the impact of rainfall on subsurface variation in groundwater quality at the topmost 10 m depth layer (Fig. 3). The other results at 14, 18, 22 and 26 m depth showed no significant impact as a result of rainfall (Table 1). Since the area receives very low rainfall and for only a short period, the impact of seepage on groundwater quality is relatively low at deeper depths. However, the groundwater below 10 m depth up to 14 m shows marginal fresh (EC = 0.7–2 dS/m) in the piezometers installed in Sakro, Belo and Sujawal, all three locations are adjacent to river Indus and at the junction of the canal system. The depth profile at Sujawal found with marginal freshwater even at the depth of 18 m which shows the seepage impact of the canal system. The higher salinity in deep soil layers (26 m) is visible in the coastal areas of Garho, KB, Chohar Jamali (CJ), Chhachh Jahan Khan (CJK), Shahbandar (SB) and Ghorabari (GB), which gradually reduces in upper soil layers and shows the progression of seawater intrusion (Fig. 5).

The data was interpreted through the interpolation method in ArcGIS. The EC data were categorized into four groundwater quality zones based on their relative EC level referring to the World Health Organization (WHO) guidelines. Zone 1, had an EC range below 0.7 dS/m, which is good quality water that is acceptable for drinking. Zone 2 had an EC range between 0.7 to 2 dS/m. The Zone 3 EC ranged from 2 to 10 dS/m. Finally, zone 4 had EC ranges from 10–25 dS/m, which is highly saline water (WHO, 2012). On average, the entire study area falls into the category of groundwater quality with moderate saline having EC values between 2 and 10 dS/m. The salinity level is unacceptable for drinking or irrigation purposes.

The water quality shown in the interpolated results (Fig. 4) for the periods of July-2017, Nov-2017 and Jan-2019, revealed two patches of freshwater that have EC values less than 0.7 dS/m. The rainfall chronological record confirms the rainfall data during those periods [40] (courtesy of Worldweatheronline.com). The trend in the rest of the interpolated results of March-2017, March-2018, and Aug-2018 shows the disappearance of those freshwater patches due to no rainfall. A similar trend is visible in the perimeter size of zone 2 which had an EC value between 0.7 to 2 dS/m. This value is acceptable for irrigation purposes. The perimeter size of zone 2 in July-2017, Nov-2017, Aug-2018, and Jan-2019 is visibly larger. It was reduced in size in the image of March-2017 and alarmingly reduced in the image of March 2018, due to the long span of drought from Aug 2017 through March 2018. This condition visible in the lower portion of the image that shows the rainfall history. The appearance of zone 4 patches (highly saline) in the lower portion of the study area (i.e. coastal marshy area) are

Table 1
EC (dS/m) values of water samples extracted from different soil layers w.r.t. time and space



	Thatta	Gharo	Sakro	Garho	KB	Belo	Sujawal	CJ	CJK	SB	Jati	GB
	Depth 10 meters											
Mar-17	1.3	1.28	0.67	4.81	11.8	0.41	1.16	8.7	2.03	12.23	10.01	8.8
Jul-17	0.8	1.11	0.51	3.7	9.9	0.34	0.81	7.2	1.98	10.1	7.4	6.9
Nov-17	0.95	1.05	0.47	3.8	10	0.34	0.82	7.3	1.75	10.3	7.8	7
Mar-18	1.24	1.21	0.52	4.1	10.47	0.42	0.9	7.8	2	12.5	9.6	7.4
Aug-18	1.01	1.2	0.49	4.09	11.01	0.38	1.01	7.6	2.01	12.34	9.21	7.4
Jan-19	1.1	1.1	0.58	4.3	11.3	0.4	1.15	7.7	1.98	11.53	10.2	8
	Depth 14 meters											
Mar-17	5.72	8.26	1.83	16.04	14.56	0.9	1.187	9	10.5	30.3	11.95	15.2
Jul-17	4.62	8.25	1.71	16	14.7	0.7	1.12	9	11	30.7	11.98	14.6
Nov-17	5.3	8.25	1.8	16.1	14.5	0.84	1.2	9	9.5	30.7	11.89	15
Mar-18	5.66	8.3	1.85	16.1	15	0.91	1.2	8.9	10.7	30.7	11.97	15.5
Aug-18	5.6	8.15	1.76	16.1	14	0.88	1.14	9.01	10.2	30.5	10.78	15.2
Jan-19	5.5	8.12	1.84	16.1	14.88	0.85	1.2	9.3	9.89	30.5	12	15.4
	Depth 18 meters											
Mar-17	6.66	8.8	3.29	29.2	32.4	3.4	1.28	10.78	11.17	45	12.86	20
Jul-17	5.27	8.7	3.3	30	32.2	3	1.15	10	11.19	45.1	13	19.8
Nov-17	6.4	8.78	3.3	29.1	32.6	3.38	1.27	10.3	11.2	44.9	12.45	20.2
Mar-18	6.5	8.7	3.3	29.3	32.5	3.43	1.3	10.5	11.2	44.9	12.85	19.9
Aug-18	6.5	8.5	3.3	29.1	32.5	3.5	1.25	10.58	11.09	45.1	11.02	19.9
Jan-19	6.68	8.9	3.26	29.4	32.5	3.43	1.28	11.04	11	45.02	13.04	20.1
	Depth 22 meters											
Mar-17	25.8	Hard rock	7.98	91.7	77.6	6	7.8	74.4	67	89.2	30.1	80
Jul-17	25.1		8	91	77.7	6	7.4	74.5	67	90.1	30.3	80
Nov-17	26		8	91.8	77.7	6.03	7.8	73	67	90.01	30.3	80.3
Mar-18	25.9		7.6	91.8	78	5.9	7.6	75	67.32	89	30.5	80.1
Aug-18	25.4		7.8	90.9	77.5	6.02	7.6	74.03	67.03	90	30.2	79.5
Jan-19	26		8	92	77.5	6.2	7.9	75.1	65.8	89.5	30.2	80.32
	Depth 26 meters											
Mar-17	38.3	Hard rock	16.1	92	87.8	22.2	30.4	84.1	90.3	91	30.5	90
Jul-17	38.6		16.1	92	87.5	22.11	30	81	90	91.06	31.2	88.7
Nov-17	38.4		16.5	92	87.6	22.2	30.5	84.8	90	91	31	88.7
Mar-18	37		16.1	92	87.7	22	30.5	84.1	90.2	91.2	30.6	88.7
Aug-18	39.1		16.23	92.9	87.7	22.3	30.4	84.2	92.02	91.02	30.5	89.05
Jan-19	38.5		16	91.9	87.2	22.1	30.3	84	90.1	90.8	30.5	88.3

due to the localized impact of sea tides and seawater intrusion. The zone 4 patches appearing on March-2018 image are displaying the impact of seawater intrusion due to the non-availability of freshwater over a longer period.

The variation in groundwater quality also presented in terms of area in km^2, which indicates the variation in the groundwater EC with respect to rainfall in the area (Table 2). The rainfall in July 2017, have a significant impact on improving groundwater quality. The continuity of rainfall in August 2017, sustains the groundwater quality up to November 2017 even there was no rainfall after August 2017. The improvement in groundwater quality of 378 km^2 was recorded with below-average rainfall which sustains 5 months period. These months are considered pre and post-monsoon season. While the same trend of groundwater improvement was observed in the data from August 2018 to January 2019. The gradual increase in high salinity spots (10–25 dS/m) in the area was observed from March 2018 due to low rainfall in Sujawal area.

The spatial variation in the groundwater EC improvement up to 0.7 dS/m in the upper 10 m layer shows the increase in the areas for drinking water, while the improvement in the zone of EC ranging 0.7 to 2 dS/m can provide the suitable root zone for plantation or cropping.

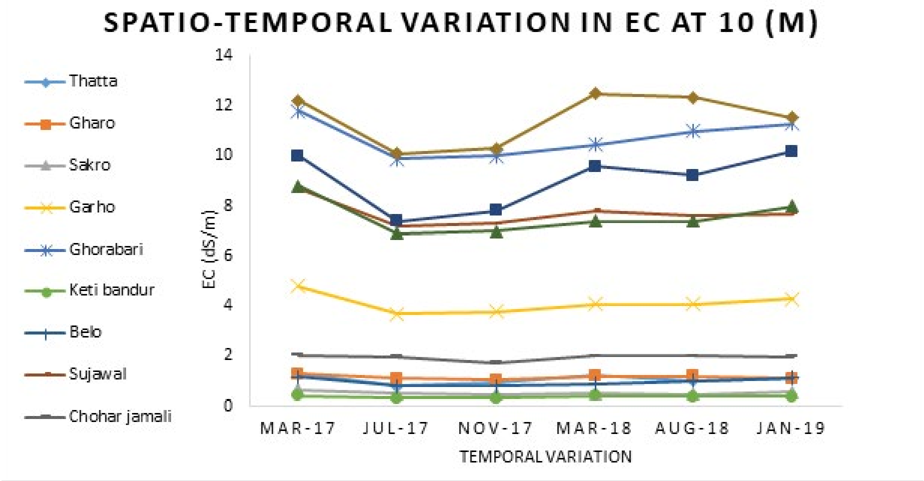


Fig. 3. Spatio-temporal variation in EC values in upper 10 m layer.

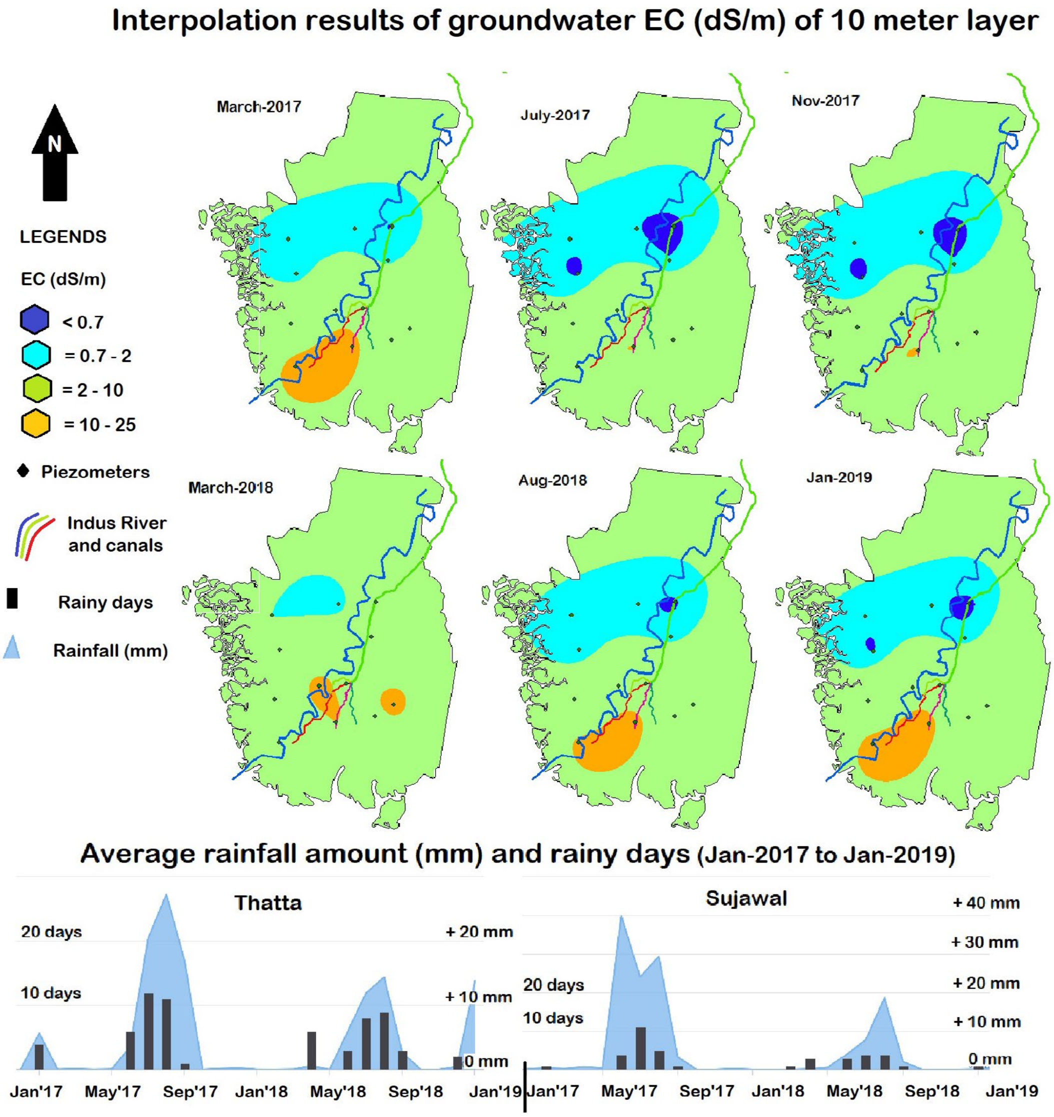


Fig. 4. Temporal distribution of rainfall and its impact on groundwater.

Table 2
Area-wise groundwater quality variation with respect to time

Date	Area in km² (total study area = 15,200 km²)			
	EC < 0.7 dS/m	EC 0.7–2 dS/m	EC 2–10 dS/m	EC 10–25 dS/m
Mar, 17	–	3,121.0	11,133.4	945.6
July, 17	378.2	4,139.0	11,682.8	–
Nov, 17	312.7	3,840.5	11,020.0	25.9
Mar, 18	–	438.0	14,326.0	436.0
Aug, 18	67.3	3,290.3	11,060.4	782.0
Jan, 19	289.1	3,372.0	10,668.6	870.3

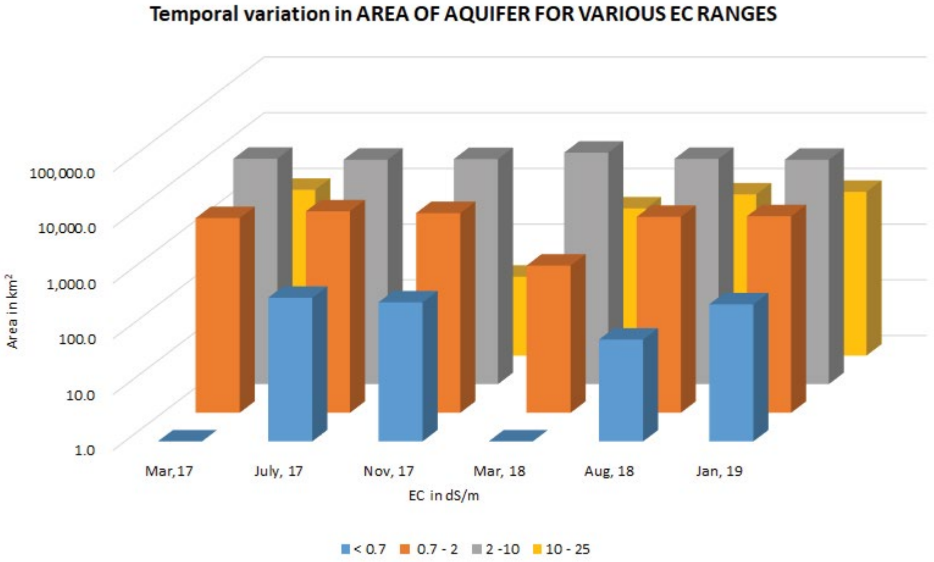


Fig. 5. Temporal variation in the area of the aquifer for various EC ranges.

5. Conclusion

Based on the tempo-spatial analysis of groundwater salinity (EC) results/values at various depths of the aquifer and presentation of the rainfall data it is concluded that even the least amount of rainfall in the study area has a positive impact on shallow groundwater quality improvement. This improvement was observed in the first 10 m. layer; however, no improvement of groundwater was observed at depths below this layer. Hence, it is suggested that periodic heavy rainfall which has a recurrence of 5 to 8 years, be retained through diverting it into lagoons and shallow wetlands, which are scattered in large area in Indus Delta and turned brackish due to scarcity in river flows The topography of the area permits the interconnectivity of most of the lagoons with river network through gravity flow [6].

The Indus Delta had slowly been degraded over the past half-century due to the gradual reduction of floodwater from the Indus River downstream from the last barrage (i.e. Kotri Barrage). The figures reveal freshwater patches, which emerged in the active irrigation areas (i.e. zone 1 and 2). This is an indication of supplementary seepage from the irrigation network and in the shallow aquifer near the Indus River. The regular flow in the earthen canals/distributaries of the irrigation network of these zones must be continuous and the practice of cultivating of high-delta crops contribute to recharging the groundwater aquifer. When these practices are re-implemented, the marginal saline aquifer will be converted into freshwater. Improving the water availability in the lagoon and shallow wetlands should also be continued to recharge groundwater.

The major issue in the research area is the prioritization and allocation of river water by Indus River System Authority (IRSA) Pakistan and unfortunately, the environmental aspect has been neglected so far and termed as the issue of Sindh province [41]. This solution needs no additional water to sustain the ecology of the Indus Delta but the management of rainwater harvesting and diverting floodwater in the rainy season may gradually improve the land degradation of Ramsar protected Indus Delta. The improvement in groundwater quality in 378 km² means the drinking water availability to approximately 38,000 persons (the population density of 100 persons/km²) for five months. With little efforts of rainwater harvesting and diverting flood-flows to natural lagoons and wetlands, the deltaic degradation can be reversed. The refreshed shallow groundwater not only resolve the drinking water problem of the entire study area but increase the reforestation of mangroves and revive the ecological cycle in the Indus Delta.

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References

[1] S. Kreft, D. Eckstein, I. Melchior, Global Climate Risk Index, Germanwatch e.V. Bonn office / Berlin office, 2017. Available at: https://www.thethirdpole.net/en/2018/03/20/pakistans-sindh-struggles-to-respond-to-climate-change-challenges/accessed 02.01.2019.

[2] M. Muzaffar, A. Inam, M. Hashmi, K. Mehmood, I. Zia, Impact of reduction in upstream freshwater and sediment discharge in Indus deltaic region, J. Biodivers. Environ. Sci., 10 (2017) 208–216.

[3] M. Waqas, M. Nazeer, M.I. Shahzad, I. Zia, Spatial and temporal variability of open-ocean barrier Islands along the Indus Delta Region, Remote Sens., 11 (2019) 437.

[4] S. Munir, A.A. Kidwai, Signature-based geospatial analysis to find out the suspended sediment concentration in Indus River Delta Pakistan, Int. J. Appl. Sci. Manage., 2 (2017) 233–245.

[5] A.A. Shah, I. Kasawani, J. Kamaruzaman, Degradation of Indus Delta Mangroves in Pakistan, Int. J. Geol., 1 (2007) 27–34.

[6] Z. Abro, A.L. Qureshi, S.M. Kori, A.A. Mahessar, Enhanced storage capacity and quality of Haleji and Hadero lakes connecting with Indus River for their sustainable revival, Pak. J. Sci. Ind. Res., 61A (2018) 35–42.

[7] A.A. Mahessar, A.L. Qureshi, K.C. Mukwana, A.Q. Jakhrani, Study of environmental impacts and threats to the Ramsar Haleji Lake, Sindh, Pakistan, Int. J. Appl. Environ. Sci., 10 (2015) 1577–1590.

[8] M.Z. Khan, T. Jabeen, S.A. Ghalib, S. Siddiqui, M.S. Alvi, I.S. Khan, G. Yasmeen, A. Zehra, F. Tabbassum, B. Hussain, R. Sharmeen, Effect of right bank outfall drain (RBOD) on biodiversity of the wetlands of Haleji wetland complex, Sindh, Can. J. Pure Appl. Sci., 8 (2014) 2871–2900.

[9] M.Y. Khuhawar, R.Z. Brohi, T.M. Jahangir, M.F. Lanjwani, Water-quality assessment of Ramsar site, Indus Delta, Sindh, Pakistan, Environ. Monit. Assess., 190 (2018) 492.

[10] A.C. Shahid, Pakistan: Indus Basin Water Strategy - Past, Present and Future, Lahore Journal of Economics, Papers and Proceedings of the Sixth Annual Conference of the Lahore School of Economics, 15 (2010) 187–211 Special Edition.

[11] SIDA, Phase 1 Final Report, Preparation of Regional Plan for the Left Bank of Indus, Delta and Coastal Zone, Sindh Irrigation and Drainage Authority, SIDA, Hyderabad, Pakistan, The Louis Berger Group Inc., 2012. Available at: http://sida.org.pk/download/reports/1.Vol-I.MainReport-Final_June_2011.pdf.

[12] N.A. Kalhoro, Z. He, D. Xu, M. Faiz, L.V. Yafei, N. Sohoo, A.H. Bhutto, Vulnerability of the Indus River Delta of the north Arabian Sea, Pak. Global Nest J., 18 (2016) 599–610.

[13] M. Qamar, M. Quraishi, Mangroves of the Active Indus Delta Changes and their Causes, A Dissertation Submitted to the School of Business Administration for Ph.D., Lambert Academic Publishing, The European Union, Latvia, 2009.

[14] G.A. Mahar, N.A. Zaigham, Spatio-temporal assessment of agriculture & mangroves and its impact on socioeconomy of people in Indus Delta, Pak. J. Bot., 51 (2019) 377–383.

[15] S. Naseem, V. Hussain, S. Bano, Origin of salinity and other constituents in Indus Deltaic Plain groundwater, Thatta District, Pakistan, J. Coast. Res., 34 (2018) 883–891.

[16] G.S. Solangi, A.A. Siyal, M.M. Babar, S. Pirah, Groundwater quality mapping using geographic information system: a case study of district Thatta Sindh, Mehran Univ. Res. J. Eng. Technol., 36 (2017) 1059.

[17] R.P. de Silva, Effect of climate change on potential groundwater recharge in the dry zone of Sri Lanka, Br. J. Environ. Clim. Change, 5 (2015) 23–36.

[18] K. Dorau, H. Gelhausen, D. Esplor, T. Mansfeldt, Wetland restoration management under the aspect of climate change at a mesotrophic fen in Northern Germany, Ecol. Eng., 84 (2015) 84–91.

[19] R.H. Moreno, A.M. Mateu, S.I. Asensio, G.J.M. Blanquer, Wetland soils under rice management and seawater intrusion: characterization and classification, Spanish J. Soil Sci., 5 (2015) 111–129.

[20] H.E. Golden, C.R. Lane, D.M. Amtya, K.W. Bandilla, H.R. Kiperwas, C.D. Knightes. H. Ssegane, Hydrologic connectivity between geographically isolated wetlands and surface water system: a review of select modeling methods, Environ. Modell. Software, 53 (2014) 190–206

[21] A.P. Dimri, D. Kumar, S. Chopra, A. Choudhary, Indus river basin: future climate and water budget, Int. J. Climatol., 39 (2019) 395–406.

[22] C.G. Ochoa, A. Fernald, S. Guldan, V. Tidwell, M. Shukla, Shallow aquifer recharge from irrigation in a semiarid agricultural valley in New Mexico, J. Hydrol. Eng., 10 (2012) 1061.

[23] P.H. Talaee, Analysis of groundwater quality in the northwest of Iran, Desal. Wat. Treat., 56 (2015) 2323–2334.

[24] H.V. Pham, S.-I. Lee, Assessment of seawater intrusion potential from sea-level rise and groundwater extraction in a coastal aquifer. Desal. Wat. Treat., 53 (2015) 2324–2338.

[25] I. Abbas, H.M. Rafique, M.A. Sohl, A. Falak, S. Mahmood, M. Imran, Y. Al-Zaghayer, A. Al-Awadi, A. Mahmood, Spatio-temporal analysis of groundwater regime within Rawalpindi Municipal Jurisdiction, Pakistan, Desal. Wat. Treat., 52 (2014) 1472–1483.

[26] N. Wolthek, K. Raat, J.A. de Ruijter, A. Kemperman, A. Oosterhof, Desalination of brackish groundwater and concentrate disposal by deep-well injection, Desal. Wat. Treat., 51 (2013) 1131–1136.

[27] A.S. Qureshi, P.G. McCornick, A. Sarwar, B.R. Sharma, Challenges and prospects of sustainable groundwater management in the Indus Basin, Pakistan, Water Resour. Manage., 24 (2010) 1551–1569.

[28] N.C. Mondal, V.S. Singh, V.K. Saxena, Improvement of groundwater quality due to freshwater ingress in Potharlanka Island, Krishna delta, India, Environ. Geol., 55 (2008) 595–603.

[29] W.J. Mitsch, J.W. Day Jr., Restoration of wetlands in the Mississipi-Ohio-Missouri (MOM) river basin: experience and needed research, Ecol. Eng., 26 (2005) 55–69.

[30] L. Giosan, S. Constantinescu, P.D. Clift, A.R. Tabrez, M. Danish, A. Inam, Recent morphodynamics of the Indus delta shore and shelf, Cont. Shelf Res., 26 (2006) 1668–1684.

[31] S. Salma, S. Rehman, M.A. Shah, Rainfall trends in different climate zones of Pakistan, Pakistan J. Meteorolog., 9 (2012) 37–47.

[32] M. Fossey, A.N. Rousseau, Assessing the long-term hydrological services provided by wetlands under changing climate conditions: a case study approach of a Canadian watershed, J. Hydrol., 541 (2016) 1287–1302.

[33] S.M. Kori, A.L. Qureshi, B.K. Lashari, N.A. Memon, Optimum strategies of groundwater pumping regime under scavenger tubewells in lower Indus Basin Sindh, Pakistan, Int. Water Technol. J., 3 (2013) 138–145.

[34] A.L. Qureshi, B.K. Lashari, S.M. Kori, G.A. Lashari, Hydro-Salinity Behaviour of Shallow Groundwater Aquifer Underlain by Salty Groundwater in Sindh Pakistan, Fifteenth International Water Technology Conference IWTC-15, Alexandria, Egypt, 2011.

[35] S. Kar, J.P. Maity, J. Jean, C. Liu, B. Nath, H. Yang, J. Bundschuh, Arsenic-enriched aquifers: occurrences and mobilization of arsenic in groundwater of Ganges Delta Plain, Barasat, West Bengal, India, Appl. Chem., 25 (2010) 1805–1814.

[36] P.G. Cook, A.J. Love, N.I. Robinson, C.T. Simmons, Groundwater ages in fractured rock aquifers, J. Hydrol., 308 (2005) 284–301.

[37] Standard Methods for the Examination of Water and Wastewater, 23rd ed., American Public Health Association (APHA) Washington, D.C., 20005, 2017.

[38] T. Wu, Y. Li, Spatial interpolation of temperature in the United States using residual kriging, Appl. Geogr., 44 (2013) 112–120.

[39] R. Ghazavi, A.B. Vali, S. Eslamian, Impact of flood spreading on groundwater level variation and groundwater quality in an arid environment, Water Resour. Manage., 26 (2012) 1651–1663.

[40] Weather Data and Graphs. Available at: https://www.worldweatheronline.com/thatta_weather_averages/sindh/pk.aspx.

[41] A.A. Anwar, M.T. Bhatti, Pakistan's water apportionment accord of 1991: 25 years and beyond, J. Water Resour. Plann. Manage., 144 (2018).