Groundwater vulnerability assessment using GIS-based DRASTIC method in the irrigated and coastal region of Sindh province, Pakistan

Asfandyar Shahab, Qi Shihua, Saeed Rad, Souleymane Keita, Majid Khan and Syed Adnan

ABSTRACT

This study aims to evaluate the vulnerability of shallow aquifer in irrigated and coastal region of Sindh province, Pakistan by applying DRASTIC method in GIS environment. Vulnerability index values ranging from 119 to 200 were categorized into three contamination risk zones. Results illustrated that 28.03% of the total area that was distributed in the upper northern and southern most coastal area of the province was very highly vulnerable to contamination, 56.76% of the area was highly vulnerable, while the remaining 15.21% area was in medium vulnerable zone. Single and multi-parameter sensitivity analysis evaluated the relative importance of each DRASTIC parameter and illustrated that depth to water table and net recharge caused the highest variation in the vulnerability index. Two water quality indicators parameters, i.e., electrical conductivity (EC) and nitrate ion (NO_3^-) were used to validate the DRASTIC index. The spatial distribution map of both parameters showed a certain level of similarity with the vulnerability map and both parameters illustrated significant correlation with the DRASTIC vulnerability index ($p < 0.01$). This signified that vulnerable zones are particularly more prone to EC and NO_3^- contamination. Findings of this study will assist local authorities in contamination prevention in the groundwater of the lower Indus Plain.

Key words | ArcGIS, DRASTIC, groundwater vulnerability, lower Indus Plain, sensitivity analysis

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INTRODUCTION

Groundwater is an important source of water for drinking, irrigation, industry, and human consumption (Shahab *et al.* 2018). In Pakistan, the consumption of groundwater has increased because of the high industrial demand, expanding agriculture, and domestic requirements and the annual groundwater withdrawal increased from 10 billion cubic meters (BCM) in 1965 to 68 BCM in 2002 (Halcrow-Ace 2003). Increasing population growth and deficiency of surface storage facilities has also resulted in elevated pressure on groundwater, consequently causing significant deterioration in both its quality and quantity (Zghibi *et al.* 2016). This problem is more severe in the irrigated and coastal area of Sindh province where seawater intrusion, poor irrigation practices, and industrial effluents have further worsened the problem. Seventy-five percent of the groundwater in Sindh is saline while 70% of tube wells pump saline water (Bhutta & Alam 2006). Such groundwater resources have diminished its value to consumers (Memon *et al.* 2011). The groundwater in Sindh has a higher chance of contamination due to excessive use of fertilizers and pesticides, poor drainage and water management practices and flat topography (Steenbergen

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et al. 2015). Vulnerability assessment studies are used to identify areas that are more susceptible to contamination. The designated area can then be targeted by proper monitoring, prevention of contaminants, and careful land use planning (Babiker et al. 2005). The presence of electrical conductivity and nitrate has often been used as an indicator of groundwater vulnerability and pollution risk assessment (Shrestha et al. 2016).

Vulnerability is categorized into specific and intrinsic vulnerability. Specific vulnerability is the vulnerability of groundwater to a contaminant and is a function of pollutant properties, anthropogenic activities, and physical parameters (Babiker et al. 2005). Intrinsic vulnerability refers to the ease with which a contaminant is added to the ground surface and can diffuse and reach the groundwater. Different methods have been proposed for the assessment of intrinsic vulnerability, which is the ability of the natural environment to provide a certain extent of protection against groundwater contamination from the surface. These methods include AVI, SYNTAC and GOD model, Iowa Ground Water Vulnerability (Hoyer & Hallberg 1991) and have been used to assess groundwater vulnerabilities in a wide range of studies (Neh et al. 2015). However, among them, DRASTIC technique (Aller et al. 1987) is the most popular, simple, and robust method, which can determine intrinsic vulnerability by ranking different hydrogeologic parameters of an area, and has been used in different studies throughout the world (Babiker et al. 2005; Neh et al. 2015; Zghibi et al. 2016; Krogulec & Trzeciak 2017). DRASTIC is an acronym of seven hydrogeological parameters, namely, depth to water table (D), net recharge (R), aquifer material (A), soil media (S), topography (T), impact of vadose zone (I), and hydraulic conductivity (C). DRASTIC is a rating and weight based method; however; this technique of assigning relative weights to attributes and ratings to descriptive entities is a significant concern in the subjectivity of this method (Neh et al. 2015).

The groundwater in the lower Indus Plain is severely vulnerable to contamination due to natural and anthropogenic perturbations. A study conducted by Alamgir et al. (2016) in Sindh concluded that the groundwater quality parameters significantly exceeded national and international standards. Similar findings were reported by Memon et al. (2011) – all four water bodies (water supply schemes, shallow pumps, dug wells, and canal water) exceeded World Health Organization (WHO) standard concentrations for coliform, electrical conductivity, and turbidity. In Sindh, groundwater quality parameters greatly exceed national and international standards where electrical conductivity (EC) varied from 2,000 to 9,000 μm/cm and TDS ranged from 1,000 to 6,000 mg/l (Mahessar et al. 2017). Groundwater samples analyzed for anions and cations in Sindh province were found to exceed standards of the WHO and Pakistan Standard and Quality Control Authority (PSQCA) rendering it unfit for drinking (Shahab et al. 2016). In the current study, groundwater contamination potential of the irrigated area of Sindh province was evaluated by a detailed investigation through the construction of a vulnerability map using the DRASTIC method. As a consequence of intensive agricultural activities, the study area is affected by waterlogging and salinity in the upper and middle Sindh region while lower southern Sindh is under the influence of seawater intrusion adjoining the Arabian Sea. To date, no single study has been reported to determine the vulnerability of groundwater to contamination in the whole lower Indus Plain which is an essential groundwater reserve for the country.

Therefore, this study is planned with the objective to identify vulnerable groundwater zones to contamination by applying the geographical information system (GIS) based DRASTIC method in the lower Indus Plain aquifer. Also, this study aims to assess the relative importance of DRASTIC parameters through sensitivity analysis for assessing aquifer vulnerability. Furthermore, the DRASTIC index will be evaluated for validity by applying two water quality indicator parameters, i.e., electrical conductivity (EC) and nitrate ion (NO_3^-). This study will eventually assist in decision-making for planners and policymakers to implement quality and standard measures to protect the depleted groundwater resource from further contamination in Sindh province.

STUDY AREA

This study is conducted in Sindh province, which constitutes the lower Indus Plain of Pakistan covering an area of about 5.45×10^{10} m^2 (5.45 million hectares) (Figure 1(a)). Hot and

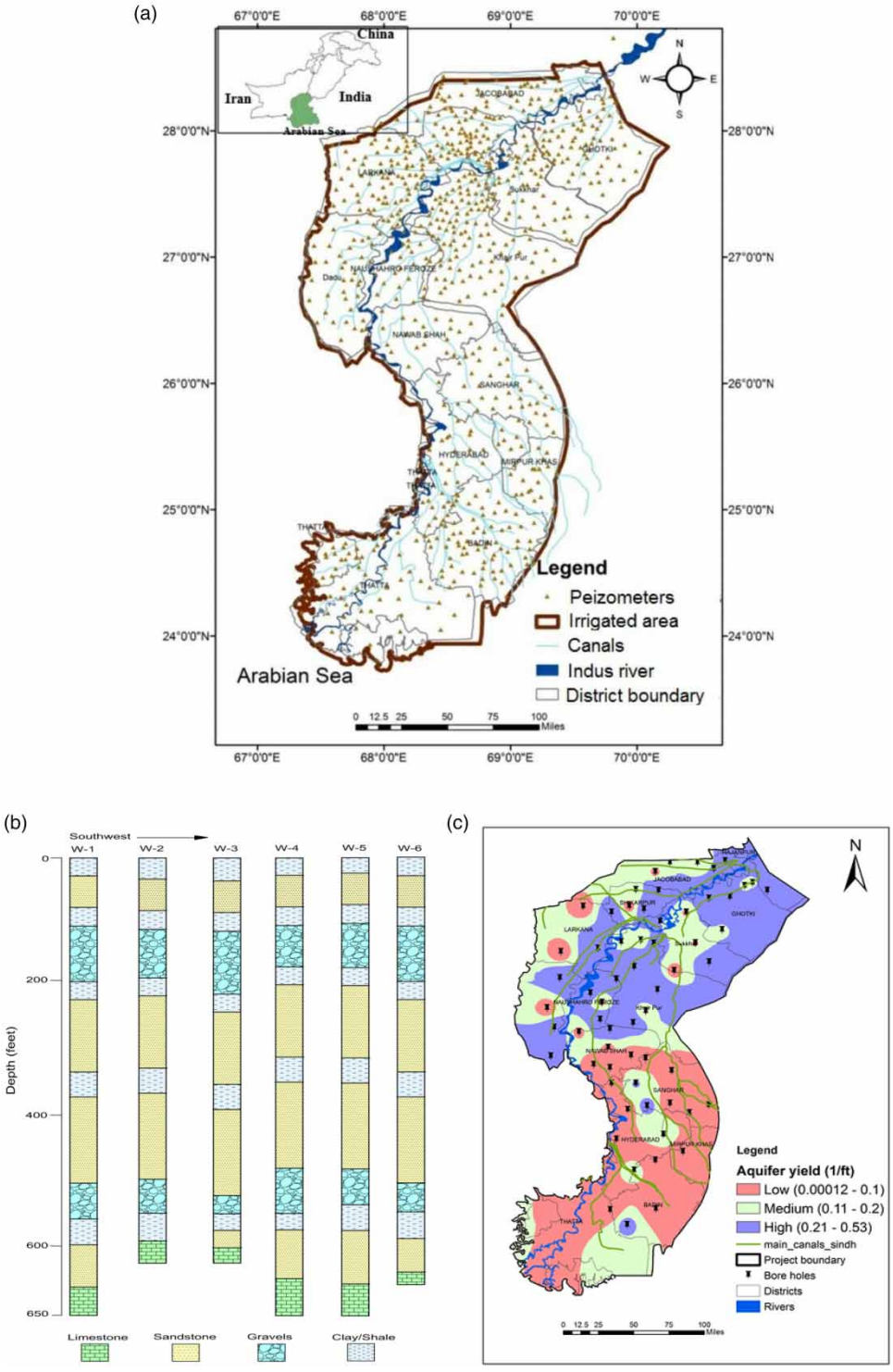

Figure 1 | Location of the study area map: (a) piezometer locations, (b) lithological cross section of bore holes in the study area, (c) aquifer yield map.

arid climate prevails in the study area where the maximum temperature exceeds 40 °C in summer and 16 °C in winter. The mean annual rainfall is within 265 mm and the evaporation rate is higher than the rest of the country. Lake

evaporation varies from 1.524 to 2.16 m/year (60–85 inches/1,524–2,160 mm) annually and exceeds 2.286 m/year (90 inches/2,286 mm) in the adjacent desert regions (Steenbergen *et al.* 2015). Agriculture in this region is mostly dependent on a canal irrigation network. Excessive use of fertilizers and agrochemicals renders the groundwater more vulnerable to contaminants.

HYDROGEOLOGY

The River Indus is the sole source of surface water which flows in the middle of the study area (Figure 1(a)). The lower Indus Plain and the irrigated area is the most critical sink for groundwater potential in Sindh province and is recharged by the rich irrigation network and meandering Indus River. The Indus River flows on a ridge and hence feeds the aquifer system alongside. The Indus River has built a distinct distributive type of fluvial system at the downstream of Sindh province, called the Indus fluvial megaridge. This fluvial system is in a convex form that shows maximum aggradation near the Indus River and gradually tapers out towards the Indus Plain edges (Giosan *et al.* 2012). The groundwater level remains high in the Indus Plain aquifer that feeds the Indus River in the Rabi season (October–March) when there is little or no flow (Steenbergen *et al.* 2015). As several barrages and dams have been constructed on the Indus River, intensive canals transfer water to 5.45 million hectares of agricultural land. Eventually water flow in the Indus River declines and is supplemented by the aquifer especially in the Rabi season as mentioned above. The groundwater, which is an underutilized resource in the irrigated area due to the fine surface water irrigation system, has resulted in water logging and salinity. The shallow groundwater aquifer is underlain by saline water which is of marine origin due to the geologic formation. In waterlogged areas, the government has combated the water logging and saline situation through vertical drainage (SIDA 2012) by launching a Salinity Control and Reclamation Project (SCARP) in the 1970s (Sindh Irrigation Drainage authority). The project recommended banning rice cultivation especially in command areas to reduce waterlogging and open drains were constructed to improve the drainage of flat areas.

Sediment depositions from the Indus River and tributaries that have formed the Indus Plain are underlain by the unconfined highly transmissive aquifer. The soil in the study area is silty and sandy loam and has become calcareous, silty clay and loamy with good porosity and weak structure (Alam & Ansari *et al.* 2000). The aquifers in the region are mainly unconfined. From a regional point of view, the aquifer of the Indus River has a single homogeneous and isotropic character, with local lithologic variations, because deeper sediments only have localized effects and do not hinder the regional movement of groundwater. The main lithology encountered in the boreholes comprised clay or shale, sandstone, gravels and some minor layers of limestone. Six boreholes were selected in a southwestern direction for lithological representation in the study area with maximum depth of 650 feet. The boreholes selected in this specific direction show almost the whole representation of the lithologies (Figure 1(b)). The clay or silt acts as an aquitard in some parts of the study area however is of less or no importance from groundwater perspectives. Based on the specific yield values an aquifer potential map has been designed which is the representative of different zones with potential varying from low, moderate to high potential (Figure 1(c)). Aquifers have high potential (0.21–0.53 ft^{-1}) on both sides of the Indus River from north towards central Sindh (until Nausheroferoz) and can provide a substantial quantity of water. The aquifer potential decreases away from the Indus River towards the western border region (at Larkana and Dadu) (0.11–0.2 ft^{-1}) while least aquifer potential prevailed from central to southern Sindh (0.00012–0.1 ft^{-1}) with little capacity to supply groundwater.

METHODOLOGY

In this study, the DRASTIC method was applied in GIS environment to evaluate the vulnerability of the lower Indus Plain aquifer in Sindh province. Delphi technique was used to assign rating and weights to the seven hydrogeological parameters used in DRASTIC method (Aller *et al.* 1987). In Delphi technique, the concerned experts rate the level of risk associated with the parameters, and a scale of the threat is established prior to the commencement of the

study. A numerical value called weight, ranging from 1 to 5, was assigned to each parameter based on its influence on the vulnerability. Thus, D, R, A, S, T, I, and C were assigned one weight value. Each of these parameters was classified into different classes and a rating ranging from 1 to 10 was assigned to each class (Table 1). Higher value corresponds to greater contamination potential because contaminants can easily penetrate groundwater, rendering it more vulnerable to contamination. Based on rating and weight, the DRASTIC index was calculated for each parameter by summing up the product of weight and rating of each parameter and used to generate maps. The vulnerability map was prepared in GIS from DRASTIC index (D_i) using the following formula:

$$\text{DRASTIC Index } (D_i) = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \quad (1)$$

where, D, R, A, S, T, I, C corresponds to depth to water table, recharge, aquifer media, soil media, topography, the impact of vadose zone, and hydraulic conductivity and r and w represent the rating and weight assigned to each parameter, respectively. Higher DRASTIC index value corresponds to higher contamination potential and vice versa. Once the DRASTIC index is calculated, it is easy to delineate areas that are more susceptible to groundwater contamination compared to others.

Data inputs and analysis of all parameters were aided by using ArcGIS 10.1. All the maps were converted into a raster format, and vulnerability was calculated for each pixel. The vulnerability map was prepared by overlying the seven thematic maps. The computed vulnerability indices for the study area were then classified into three classes by a fixed area percentage interval.

Table 1 | Rating and weights of DRASTIC parameters

Parameters	Ranges/classes	Rating (r)	Index (D)	Area covered (%)
Depth to water table (D) (m)	<1.5	10	50	49.6
	1.5–4.5	9	45	25.8
	4.6–8.5	7	35	24.6
	Weight 5			
	<250	7	28	8.4
Net recharge (R) (mm/yr)	251–300	8	32	27.5
	301–350	9	36	36.9
	>350	10	40	27.2
	Weight 4			
Aquifer media (A)	Fine to med sandstone	5	15	27.4
	Med course sandstone	7	21	53.2
	Gravel	8	24	18.3
	Limestone	9	27	1.1
	Weight 3			
Soil media (S)	Clay	1	2	10.2
	Silty clay	2	2	33.3
	Sandy clay	3	6	43.9
	Loamy	5	10	11.3
	Sandy	8	16	1.2
	Weight 2			
Topography (T) (%)	0–1.5%	10	10	83.2
	1.5–2%	8	8	15.1
	>3%	5	5	1.7
	Weight 1			
Impact of vadose zone (I)	Sandy	8	40	49.7
	Silty clay	3	15	8.6
	Clay	2	10	3
	Sandy clay	5	25	38.7
	Weight 5			
Hydraulic conductivity (C) (m/d)	<30	5	15	37
	30–45	6	18	38.9
	45.1–60	7	21	18.9
	60.1–91.6	9	27	5.89
	Weight 3			

Note: m corresponds to meter, mm/yr is millimeter per year, m/d corresponds to meter per day.

CONCEPTUALIZATION OF DRASTIC PARAMETERS

Preparation of the DRASTIC vulnerability map requires multidisciplinary data. These include groundwater level, soil type, hydrogeological data, precipitation, and seepage data. Soil data and boreholes' data of 101 litholologs were acquired from the International Waterlogging & Salinity Research Institute (IWASRI) and Water and Power Development Authority (WAPDA) Pakistan. Depth to water table and hydrogeologic data (aquifer media and impact of vadose zone) were extracted from the boreholes' data. Recharge was calculated from various sources including canals outflow, tube wells pumpage, distributaries, and watercourses, for which, required data were acquired from the Pakistan Council of Research in Water Resources (PCRWR) Islamabad and then average annual net recharge

was calculated. Precipitation data were acquired from the Pakistan Meteorological Department (PMD). Finally, all data were compiled and processed in ArcGIS to generate maps.

Depth to the water table (D)

This an important parameter in DRASTIC assessment study as it regulates migration of various materials infiltrating with water prior to reaching the saturation zone. Water level data were obtained from 369 piezometers that are under the observation of IWASRI (Figure 1(a)). The data were collected from 2001 to 2013 and mean value was calculated. Inverse distance weighted interpolation technique in ArcGIS was applied to generate depth to water table map. The generated map was then reclassified into three ranges and a rating was given based on their contribution to vulnerability. Higher rating corresponds to higher vulnerability of the aquifer to contamination and vice versa. The highest weight of 5 was assigned to 'D' parameter due to its high significance in the vulnerability study. Index for D was prepared by multiplying rating and weight, which was then used to generate a map in Arc.GIS software. The index for D was obtained from the product of weight and rating (Dr × Dw) (Aller *et al.* 1987).

Recharge is an important component as it is responsible for transporting contaminant from the surface to the water table. It is directly proportional to vulnerability rating and contamination (Zghibi *et al.* 2016), therefore, numeric weight 4 was assigned due to its high impact on vulnerability. Accurate recharge calculation is complicated; therefore, all the recharge sources were determined for recharge computation. The main recharge sources in the study area includes rainfall, inflow from the River Indus, seepage from pumpage, and recharge from the irrigation system (canals, distributaries, watercourses, and irrigated fields). Average annual recharge from these sources was calculated by using the following formula (Usman *et al.* 2015):

$$\Delta S = L_{es} + (GW_{in} - GW_{out}) + IRF + RFR - GW_p \quad (2)$$

where, ΔS is the change in ground water storage/recharge, L_{es} is the seepage loss from irrigation network to groundwater, IRF is the irrigation return flow from field and RFR is the rainfall recharge, GW_{in} and GW_{out} are the lateral groundwater in and outflow in the study region, and GW_p is groundwater abstraction by pumping. All units are in mm per unit time.

$$IRF = I_{FF} \times D_f \quad (3)$$

where, IRF is irrigation recharge from fields, I_{FF} is the total irrigation water supplied to farms, and D_f is the fraction of groundwater contributing to recharge

$$GW_p = 0.000036 \times \text{NPTW} \times \text{UTF} \times \text{AD} \times \text{TOH} \quad (4)$$

where, GW_p is groundwater pumpage by tube wells, 0.000036 = conversion factor, NPTW is the number of tube wells, UTF is utilization factor for each month, AD is actual discharge (m^3/s), and TOH is the total operational hours in a year (h):

$$RFR = 20\% \textit{ of total rainfall} \quad (5)$$

where, RFR is the recharge from rainfall.

Based on all these computations, average annual recharge was calculated and categorized into four classes. Finally, a recharge map was generated in ArcGIS by interpolating those average annual recharge rates. Higher rating (10) was assigned to highest recharge zone while rating 7 was assigned to the least recharge zone.

The aquifer media and impact of vadose zone map layer were prepared from the lithology of boreholes. Due to their importance in the vulnerability study, numerical weights 3 and 5 were assigned, respectively. Sand, gravel, and limestone constituents of the aquifer media and vadose zone were assigned high ratings due to high permeability and contaminant transport potential.

The soil map was prepared based on the information of soil types provided by IWASRI. Those soil types were digitized in ArcGIS and a corresponding rating from 1 to 10 was assigned to each soil type based on its permeability. The major constituents of soil in the study area are sandy clay and silty clay with patches of clay and loamy soil type. The coarse soil media, such as sandy soil which has greater potential for contaminant transport, were assigned the highest rating 8 as compared to fine soil media (clay)

which has poor potential for contaminant migration and was assigned rating value 1. A numeric weight value 2 was assigned to soil media based on its impact in the vulnerability to contamination.

Topography, which refers to the slope of an area, was calculated from 90 m digital elevation model (DEM) in GIS using the following formula (Babiker *et al.* 2005):

$$Slope\% = \left(\frac{HYP(D_x, D_y)}{PixcelSivadoseze}\right) \times 100 \quad (6)$$

where, *HYP* is a map calculation function of ILWIS which calculates the positive root of the sum of square $D_x + D_y$ (Pythagoras rule), and D_x and D_y represent the horizontal and vertical gradients, respectively.

Slope was then categorized into different ranges and a rating from 1 to 10 was assigned to each range. Flat areas were assigned the highest rating (10) as they allow more time for the contaminant to percolate down to the aquifer system, while steep areas increase the runoff, reducing the infiltration and thus assigned low rates. Weight 1 was assigned to slope parameter for contributing the least impact to vulnerability.

Hydraulic conductivity, which refers to the ability of the aquifer to transmit water, was computed by pumping test method (Jacob 1946) based on aquifer type. High rating corresponds to higher conductivity zones due to their high potential for contaminant transportation (Rahman 2008). Weight 3 was assigned based on its importance in vulnerability studies. Maximum rating 9 was assigned to the highest conductivity zone while low conductivity was rated 5.

The DRASTIC vulnerability index map was computed based on Equation (1). To understand the vulnerability index, the DRASTIC index score was first classified into three ranges based on the vulnerability index score, i.e., medium vulnerable zone, high vulnerable zone, and very high vulnerable zone, respectively.

SENSITIVITY ANALYSIS

In the DRASTIC method, many data inputs layers can be assessed, which makes it more advantageous over other vulnerability assessment methods (Evans & Myers 1990) and could minimize the impacts of individual parameters' uncertainties on the final output. Napolitano & Fabbri (1996) reported that the ratings and weights technique adopted in DRASTIC is subjective, and there is no ambiguity in the methodology and accuracy of the calculated vulnerability index. However, some may still doubt the reliability of results as the methodology lacks experimental evidence (Rahman 2008). To reduce the concerns, sensitivity analysis was carried out using two methods, map removal sensitivity analysis and parameter sensitivity (Weldon *et al.* 1990) which evaluate the accuracy of results (Babiker *et al.* 2005).

Map removal sensitivity analysis

Map removal analysis can be used to find the sensitivity of the index while removing one or more DRASTIC parameters (Lodwick *et al.* 1990). The sensitivity measure regarding variation index was achieved by removing one or more map layers using the following equation:

$$S = \frac{(|(V/N) - (V'/n)|)}{V \times 100} \quad (7)$$

where, S is the variation index, V is perturbed vulnerability index representing the actual index as in the primary suitability using (N) parameters, and V' is the perturbed vulnerability index with a lower number of parameters (n) used.

Two types of analyses were conducted. In the first, a single layer was removed at a time, considering every parameter constituted in the DRASTIC method. The primary aim of this step was to evaluate the sensitivity of vulnerability values by removing a defined parameter. In the second analysis, map layer, which has minimum contribution in the variation index, was removed followed by the removal of the next less effective layer. The same steps were continued until a single useful layer was left.

Single parameter sensitivity analysis

Impact of each parameter in the vulnerability index was identified in single parameter sensitivity analysis. This

analysis is essential since the DRASTIC index is highly sensitive to parameter weighting and scores and numerical weights assigned to the parameters are mainly subjective (Saidi *et al.* 2010). Single parameter sensitivity analysis compares the effective/real weight of each input parameter with that of theoretical weight (Saidi *et al.* 2010) in each polygon and is computed as:

$$W = (P_r \times P_w / V) \times 100 \quad (8)$$

where, W is the effective weight of each parameter, P_r and P_w are the respective rating and weight of each parameter, and V corresponds to the overall vulnerability index.

RESULTS AND DISCUSSION

DRASTIC parameters and vulnerability map

Based on the methodological application, a thematic map for each parameter and a vulnerability map were prepared to evaluate the risk and vulnerability associated with groundwater in Sindh province. Vulnerability results of each parameter are discussed below.

Depth to water table ranged from <1.5 metre (m) to 8.5 m from the surface in the study area. D map prepared by interpolation was further divided into three categories based on water level, i.e., <1.5 m, 1.5–4.5 m, and 4.6–8.5 m, covering 49.6%, 25.8%, and 24.6% of the area, respectively (Table 1 and Figure 2). Maximum rating 10 was assigned to the most shallow water table zone which prevailed mostly in northern Sindh (Jaccobabad, Shikarpur, Larkana) and southern Sindh coastal area (Thatta and Badin) while 9 and 7 ratings were assigned to the other two zones corresponding to water level 1.5–4.5 m and 4.6–8.5 m, respectively. Due to its high potential in vulnerability, a weight value 5 was assigned to D parameter. It is inferred from the map (Figure 2) that mostly shallow water level prevailed in the whole irrigated area and southern coastal zone of Sindh province. These areas are highly vulnerable, as pollutants are required to travel a shorter distance to reach the water table (Krogulec & Trzeciak 2017). High recharge rate was observed in the study area despite low rainfall, which is possibly due to the rich canal irrigation network, the River Indus, and seawater intrusion. Numeric weight value 4 was assigned to the net recharge parameter. The recharge map (Figure 3) illustrates that districts Hyderabad and parts of district Thatta and Badin represent high recharge zone with more than 350 millimetre per year (mm/yr) while 644 mm/yr recharge rate was observed at district Khairpur, therefore, the highest rating 10 was assigned to these areas due to high contamination potential. The least recharge zone was assigned rating 7 in Dadu district bounded by Kherthar range that separates Sindh from Baluchistan province. Qadir *et al.* (2014) reported that recharge in the Indus Basin increased by 0.64 m from 1976 to 1996 due to irrigation. In fresh groundwater quality zones in all canal commands of Sindh, the groundwater balance shows net increases due to recharge (Rehman 1998).

The aquifer media, weighted as 3, primarily contained a mixture of sand and gravel as a major component. Fine to medium sand covering 27.4% of the area was assigned rating score 5 while the medium coarse sandstone which covered 53.2% of the area was assigned rating 7. Similarly, limestone and gravel were assigned higher rating 9 and 8 because of higher porosity potential (Table 1 and Figure 4). This zone characterizes a high vulnerability index implying that a contaminant can be easily transported to the aquifer through the soil (Zghibi *et al.* 2016).

The major constituents of soil media were sandy clay, silty clay, loam, and clay (Figure 5) covering 43.9%, 33.3%, 11.3%, and 10.2% of the area, respectively (Table 1). The presence of fine-textured materials such as clay and silt which decreases the relative permeability of the soil and hinders percolation of contaminants (Saidi *et al.* 2010) were assigned a lower rating compared to sandy soil which has high porosity and can increase the aquifer vulnerability (Akhtar *et al.* 2014). Sandy clay was mostly distributed in the central and lower southern parts of the region (Dadu, Nosherferoz, and Thatta) while clay and silty clay was the major soil composition in the upper northern Sindh region (Jaccobabad, Ghotki, and Sukkur), and partially in district Sanghar and Badin areas. Loam and clay were in patches of upper and middle Sindh areas. Numeric weight value 2 was assigned to soil media parameter.

The topography of Sindh is flat. Slope varies from 0 to 3% in the irrigated area of Sindh (Figure 6). Owing to its

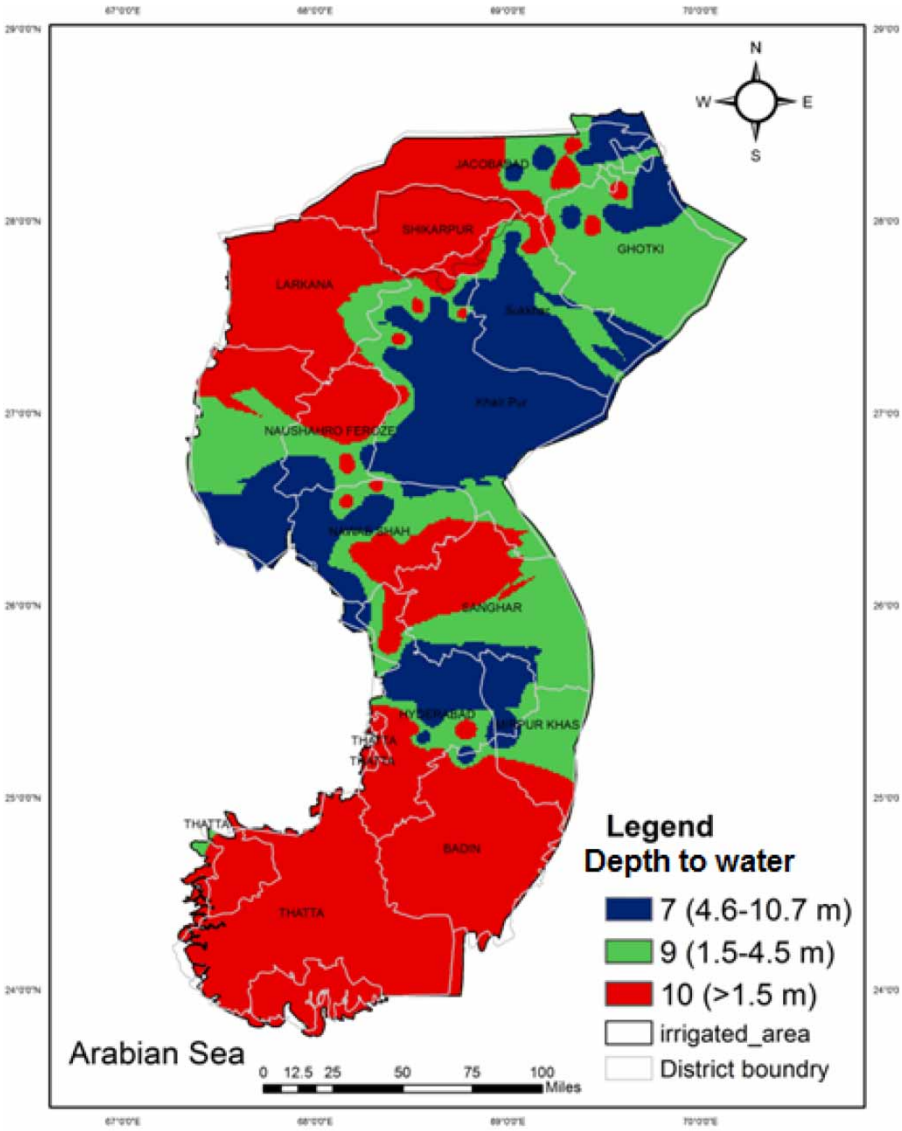

Figure 2 | Depth to water table (D) map.

impact on vulnerability, weight value 1 was assigned to topography. The highest rating 10 was assigned to the flat area (slope <1.5%) which covers 83.2% of the total area because flat areas reduce the runoff allowing more time for percolation of contaminants into the aquifer. Ratings 8 and 5 were assigned to the slope class ranging from 1.5 to 2% and <3% covering 15.1% and 1.7% of the total area, respectively (Table 1), reflecting moderate and low vulnerability impact on groundwater.

Due to shallow aquifer and high water table, a thin vadose zone persists in the study area, rendering the groundwater more vulnerable to contamination. Sand was the major component of the vadose zone which covers 49.7% of the area followed by sandy clay covering 38.7% of the area (Table 1). Due to their high contribution to groundwater vulnerability, high ratings of 8 and 5 were assigned (Figure 7). Clay and silty clay which have the characteristics of low porosity and less contribution to the vulnerability, were sparsely distributed in the vadose zone and were assigned low ratings of 3 and 2, respectively. A weight factor 5 was assigned to the vadose zone owing to its importance in the DRASTIC index.

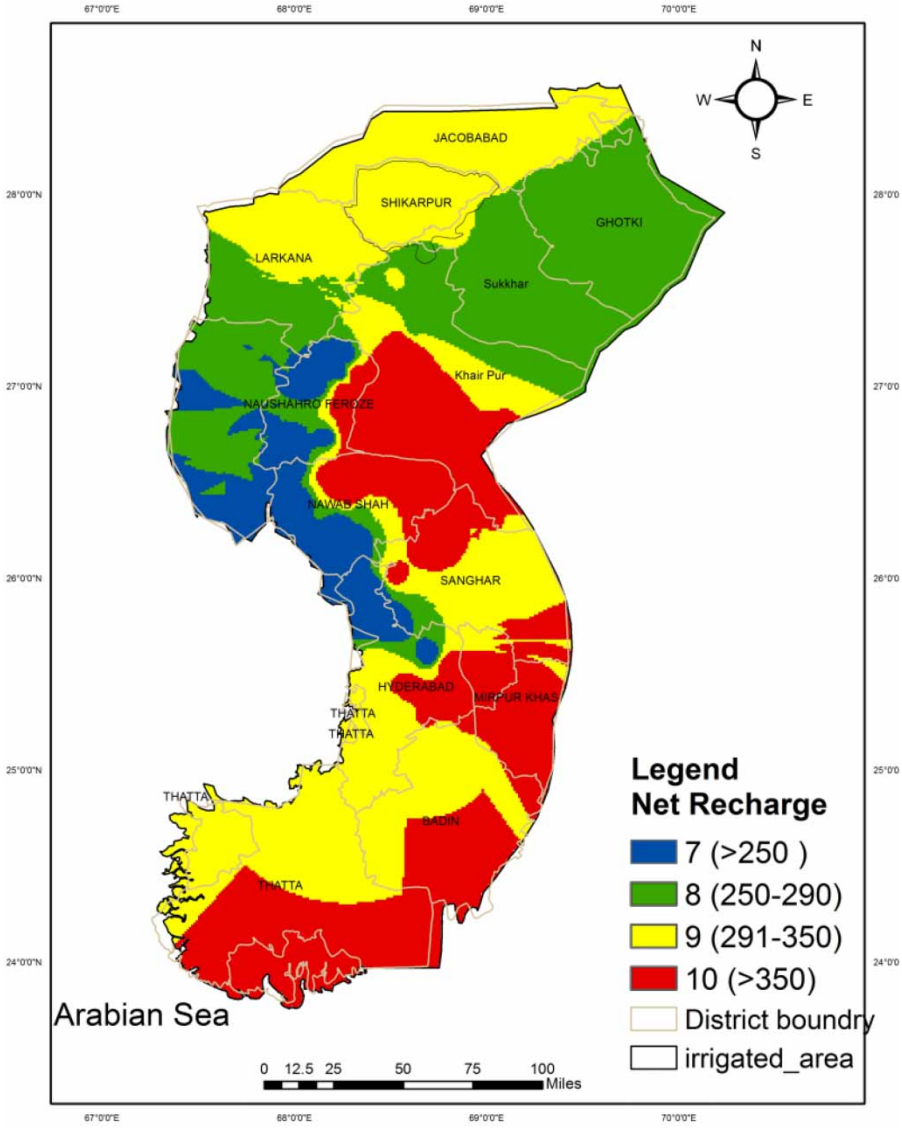

Figure 3 | Net recharge map (mm/yr).

Hydraulic conductivity is the potential of aquifer materials to transmit water and determines the rate of groundwater flow. Hence, it regulates the diffusion of contaminants to the aquifer from the soil surface. If the hydraulic conductivity is high, the vulnerability of the aquifer is considered high. Based on pumping test values of boreholes, hydraulic conductivity values that ranged from 19 to 91.6 m/d in the study area were divided into four different zones (Figure 8). The highest conductivity zone (60.0 meter per day (m/d) to 91.6 m/d) was distributed in the upper northern Sindh (Jacobabad and Ghotki districts) and the highest rating 9 was assigned due to its high potential for contaminants' transport to the aquifer. Southern Sindh, which constitutes the area from Hyderabad to the coast of the Arabian Sea, covering 37% of the total area, was assigned the lower rating 5 owing to lower hydraulic conductivity (<30 m/d). This result is consistent with the aquifer yield map (Figure 1(c)) illustrating lower aquifer potential in southern Sindh towards the Arabian Sea.

Based on Equation (1), DRASTIC index was calculated by combining all seven layers, and a vulnerability map was prepared based on DRASTIC index (Figure 9).

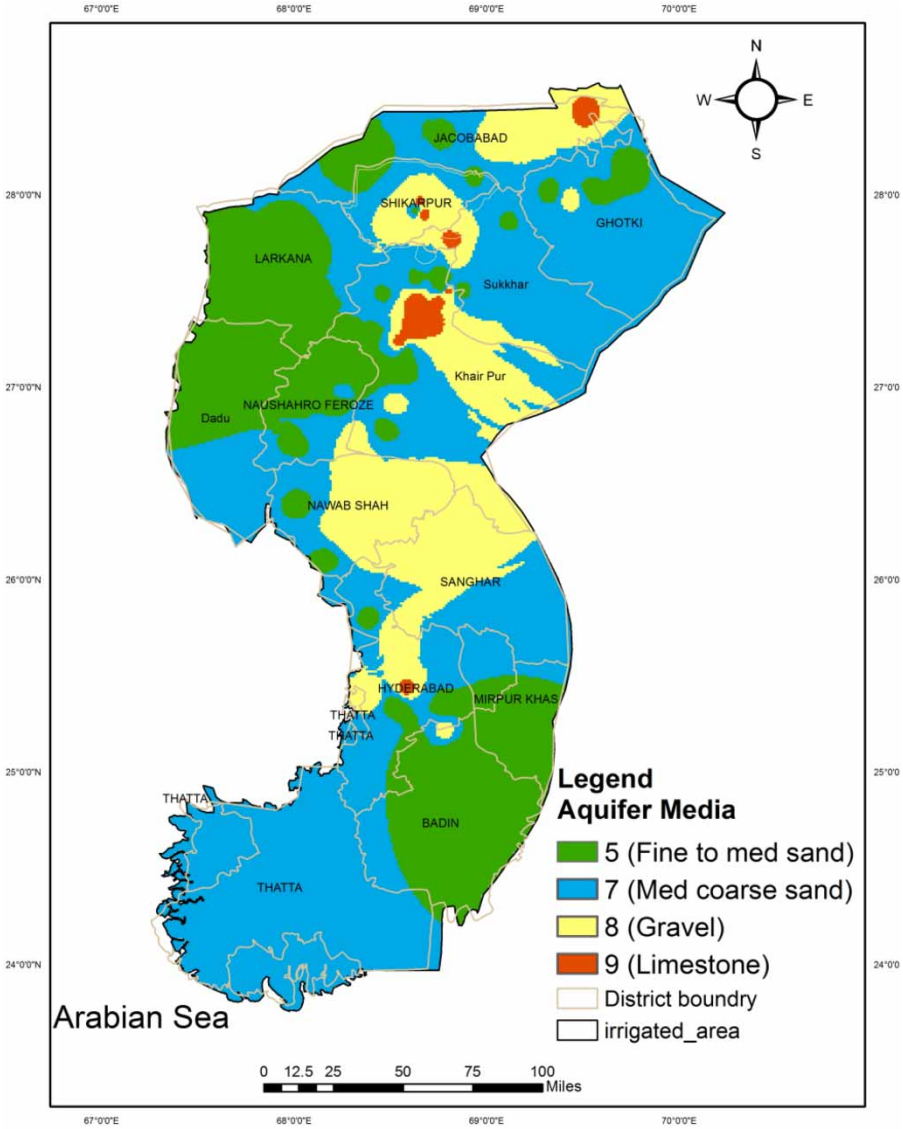

Figure 4 | Aquifer media map.

The aquifer vulnerability map was then categorized into three classes, medium vulnerable (119–145), high vulnerable (145–165), and very high vulnerable zones (166–200). In the DRASTIC vulnerability map of the study area, it is noteworthy that 'no risk zone' which corresponds to the index value less than 100 (Rahman 2008; Al-Rawabdeh 2013; Akhtar *et al.* 2014) did not exist in the study area, indicating groundwater is highly vulnerable to contamination. The medium vulnerability zone was found in patches in districts Dadu and Sukkur and in Sanghar district covering 19.50% of the area. In fact, a comparatively deeper water table and lower recharge rates prevailed in these areas, which make them medium vulnerable zones. The high vulnerable zone was mostly dominant in northern and central Sindh, including Ghotki, Larkana, Nausheroferoz, Khairpur, Nawabshah (Benazirabad), and Hyderabad, covering 52.19% of the total area. One of the main reasons for this high vulnerability is the presence of extensive paddy rice cultivation, which remains inundated throughout the season, eventually lead to waterlogging (Steenbergen *et al.* 2015). Rice canal, Begari Sindh feeder, Khairpur

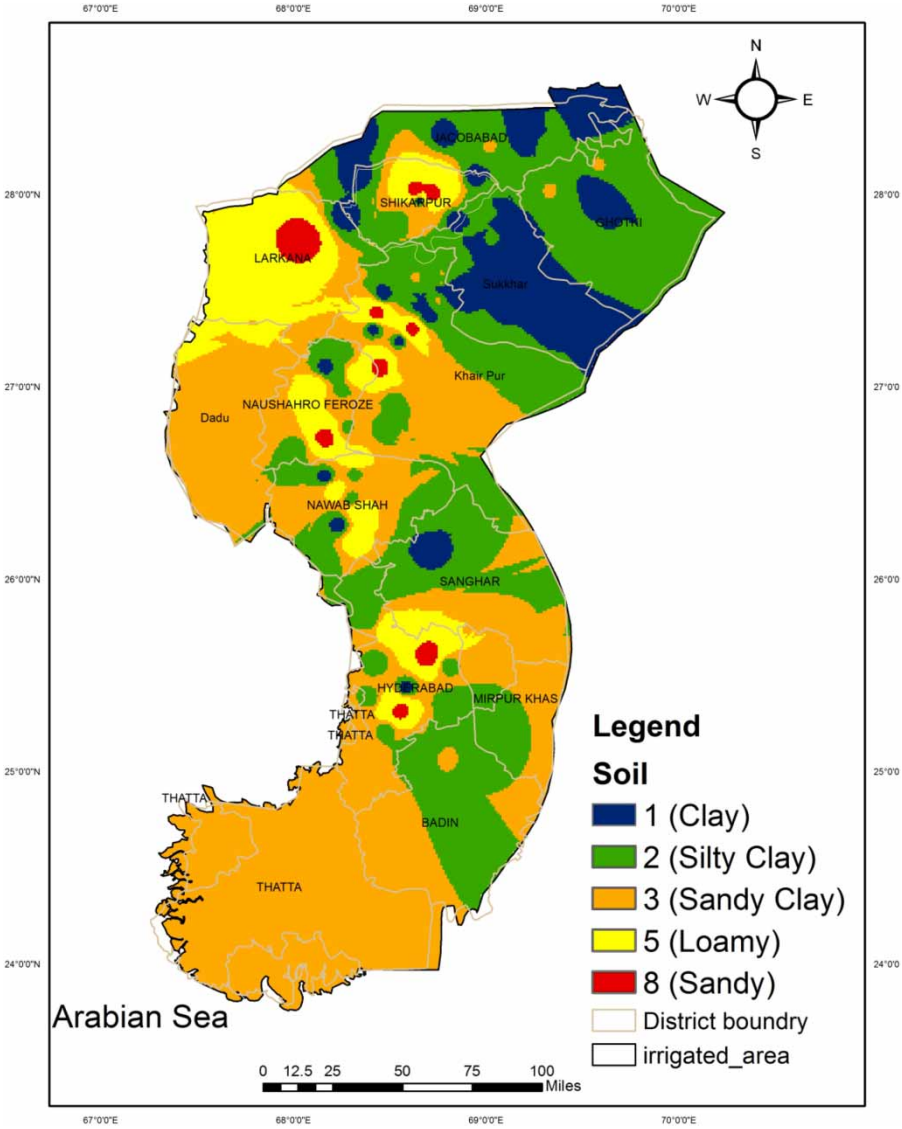

Figure 5 | Soil media map.

west canal, Rohri canal, and North West canals are concentrated in the central Sindh region to irrigate the farms consistently. The very high vulnerable zone constituted 28.13% of the whole area and was distributed in the northern parts of Sindh province (district Jacobabad and Shikarpur) and southernmost coastal part (Thatta and Badin) that adjoins the Arabian Sea. The lower left bank area of Sindh (Thatta and Badin) is under severe water management disaster even by international standards. Waterlogging and salinity persist due to high erratic irrigation water supplies and natural worsened drainage due to tidal effects as well as flat topography (SIDA 2012). The disastrous impacts are not only limited to agriculture but also render the groundwater unfit for drinking (Memon *et al.* 2011). Similarly, the intensive agriculture activities, especially rice cultivation which is inundated by water for almost its entire growth period in the upper Sindh areas including Larkana, Shikarpur, and Jacobabad, render the area waterlogged. Another possible reason is the limited use of groundwater through tube wells due to the rich irrigation canal network (Saeed & Mehboob 2011).

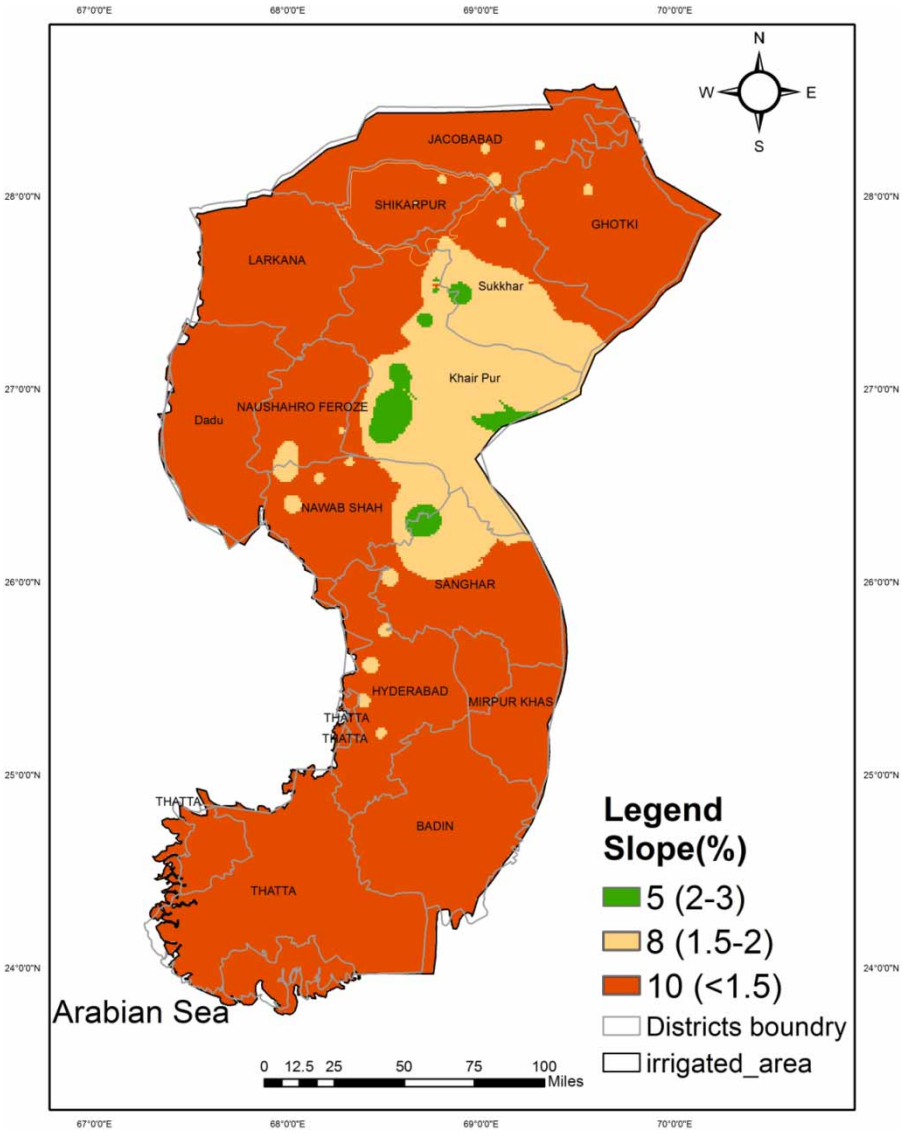

Figure 6 | Slope (topographic) map.

Sensitivity of the DRASTIC method

Descriptive statistics (min, max, sum, mean, standard deviation (SD), and variance coefficient (CV%) of the DRASTIC parameters are given in Table 2. The highest risk of groundwater contamination in the Sindh province was associated with slope, net recharge, and depth to water table (mean values 9.03, 8.67, and 8.18). These results are logical as the topography of Sindh province is mostly flat with little variation and the southern part of the province adjoins the Arabian Sea, rendering the area waterlogged (Memon *et al.* 2011). Also, recharge in Sindh province is highest compared to other provinces of Pakistan due to the rich irrigation canal network. Furthermore, groundwater is underutilized in Sindh province (4.3 billion cubic meter (BCM)) (Halcrow-Ace 2003) for two main reasons: first, the provisions of rich canal irrigation supplies, and second, a substantial portion of saline groundwater (Steenbergen *et al.* 2015). The results of the sensitive analysis are in agreement with the findings of Rahman (2008). A groundwater vulnerability study conducted by Akhtar *et al.* (2014) in Lahore, Pakistan, also reported highest risk associated with

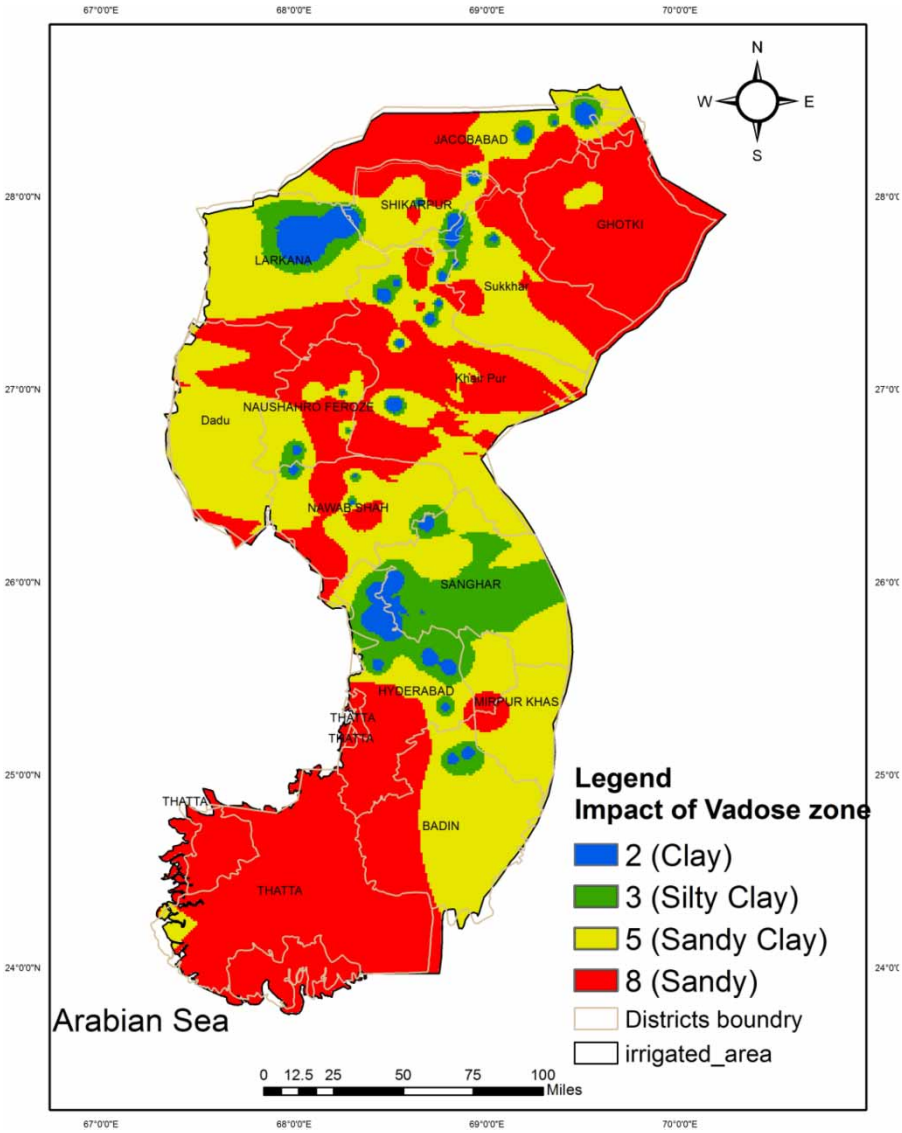

Figure 7 | Impact of vadose zone map.

topography and aquifer media. Moderate contamination risk is associated with aquifer material (6.624), impact of vadose zone (5.55), and hydraulic conductivity (6.39) (Table 2). Soil poses minimum risk (2.75) and is due to the occurrence of clay materials that provide a certain level of protection eventually reducing contamination risk. Soil media have high variability (CV% 72), the impact of the vadose zone has medium variability (CV% 44.68) while the rest of the parameters poses low variability. High variability corresponds to greater variation in vulnerability index and vice versa (Zhgibi *et al.* 2016).

Map removal sensitivity analysis

Map removal sensitivity analysis based on Equation (7) was computed by removing one or more map layers (Tables 3 and 4). Removing one layer at a time did not illustrate a significant variation in the vulnerability index (Table 3) as variation indices' values of parameters were close to each other and the difference did not exceed 1%. However, high relative variation in the vulnerability index was observed (1.98%) by removing depth to water table parameter from the computation which could be due to its

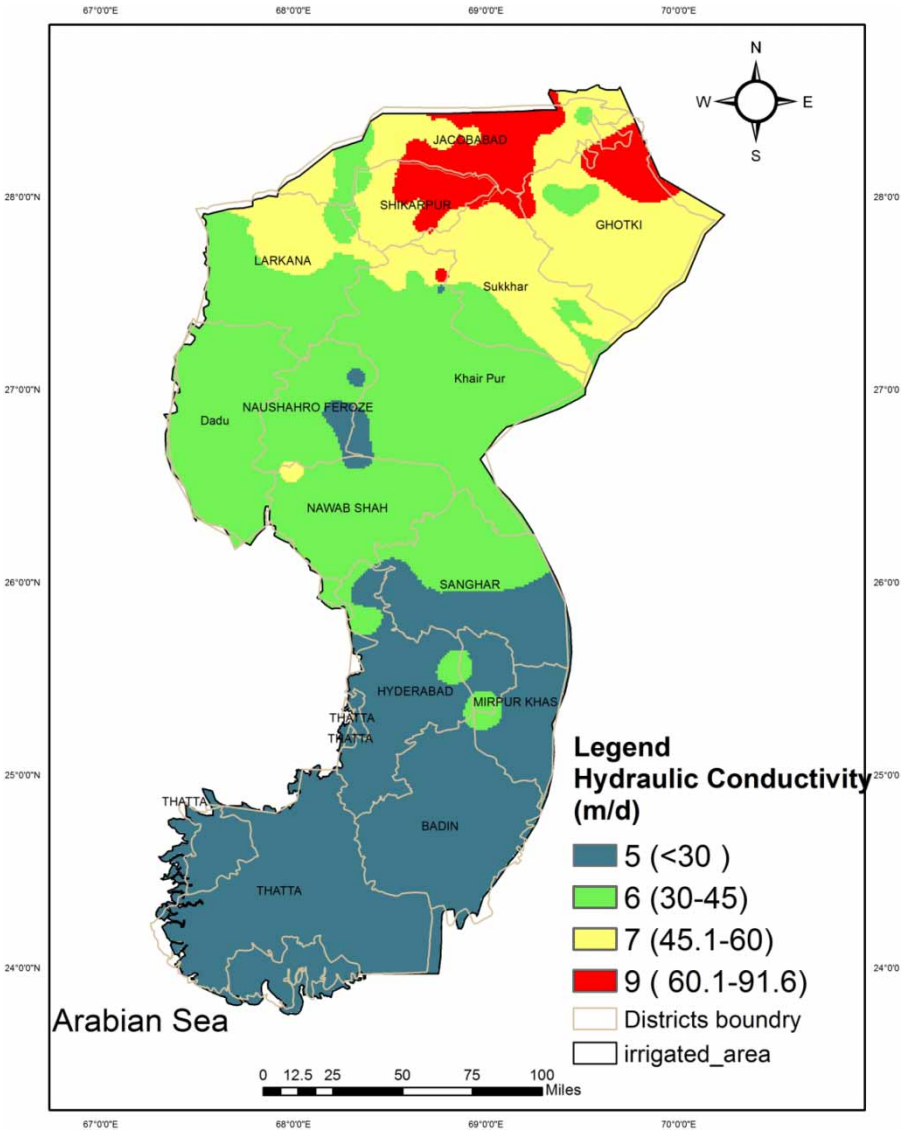

Figure 8 | Hydraulic conductivity map.

relatively higher theoretical weight 5 (Table 1). This could mainly reflect the importance of depth to water in this vulnerability study. A high contamination risk (mean risk rating 8.18) is associated with the shallow water table (rating 10) which is the main characteristic of the lower Indus aquifer. Furthermore, vulnerability index was also sensitive to the removal of soil parameter (mean value 1.81%) (Table 3) despite its low theoretical weight (2). However the reason could be its maximum variation (72%) in the variation index (Table 2). This signified that constituents of soil media play an essential role in the vulnerability of the lower Indus aquifer. Moreover, topography (1.41%), recharge (1.3%), and impact of the vadose zone layer (1.1%) are also relatively necessary parameters in the vulnerability index. Overall, the variation index sequence is $D > S > T > R > I > A > C$ which is different from the pattern of their magnitudes based on theoretical weight, $D > I > R > A \geq C \geq S > T$. The coefficient of variation, mean rating score, and theoretical weight govern these variations in the variation index (Rahman 2008).

While removing multi-parameters, the least mean variation was obtained after removal of soil parameter (1.8%)

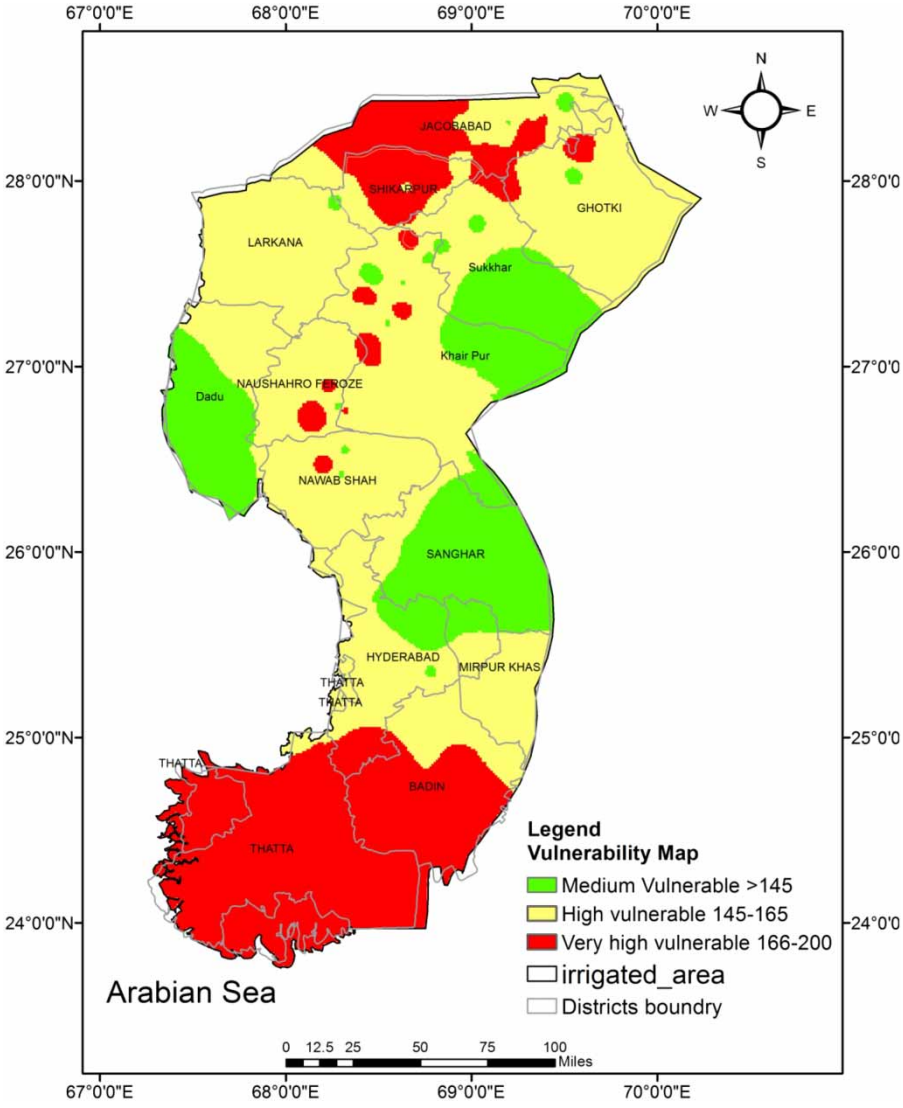

Figure 9 | DRASTIC vulnerability map.

Table 2 | Statistical summary of risk associated with DRASTIC parameters

Statistics	Depth to water table	Recharge	Aquifer	Soil	Slope	Vadose	Conductivity
Minimum	7	7	5	1	5	2	5
Maximum	10	10	9	8	10	8	9
Sum	827	876	669	278	912	561	646
Mean	8.18	8.67	6.624	2.75	9.03	5.55	6.39
SD	1.123	1.006	1.43	1.98	1.48	2.48	1.25
CV%	13.73	11.60	21.59	72	16.39	44.68	19.56

SD, standard deviation; CV%, percent coefficient of variance.

Table 3 | Map removal sensitivity analysis (one parameter is removed)

	Variation index (%)			
Parameters removed	**Min**	**Max**	**Mean**	**SD**
D	0.93	3.37	1.98	0.54
R	0.24	2.52	1.33	0.51
A	0.016	1.11	0.49	0.29
S	0.48	2.19	1.81	0.38
T	1.014	1.86	1.42	0.17
I	0.014	2.15	1.10	0.55
C	0.025	1.13	0.45	0.27

D, R, A, S, T, I, C corresponds to depth to water table, net recharge, aquifer media, soil media, topography, impact of vadose zone and hydraulic conductivity. SD, standard deviation.

from the sensitivity analyses (Table 4). The mean variation index follows a regular and increasing trend after removal of the next least impressive parameter subsequently by the removal of topography, hydraulic conductivity, aquifer material, impact of vadose zone, and finally, net recharge. Depth to water table was found to be the most influential parameter in the sensitivity analysis of the lower Indus irrigated area having the highest impact on the variation index with mean value of 11.9% and is in accordance with the findings of Krogulec & Trzeciak (2017). Furthermore, these findings revealed that it is imperative to use all seven parameters to determine the vulnerability of an area. In this study, the high and low vulnerability pattern is mainly dictated by the depth to water table, also by the findings of Babiker *et al.* (2005). Shallow water table that is classified as very high vulnerable zone prevailed in the upper and southern Sindh area while comparatively deeper water level exists in Dadu, Khairpur and parts of district Sanghar and they are classified as medium vulnerable zone in the vulnerability map (Figure 9).

Table 4 | Map removal sensitivity analysis (one or more parameter removed at a time)

	Variation index (%)			
Parameters removed	**Min**	**Max**	**Mean**	**SD**
DRATIC	0.47619	2.19	1.81	0.38
DRAIC	2	4.83	3.87	0.50
DRAI	3.007	7.3	5.33	0.82
DRI	2.05	9.74	6.4	1.57
DR	4.75	15.37	9.93	11.88
D	5.6	20.2	11.9	3.24

Single parameter sensitivity analysis

Based on Equation (8), single parameter sensitivity analysis was computed to compare the effective weight with the theoretical weight of DRASTIC parameters. Theoretical weight is the assigned DRASTIC index weight to each parameter while effective weight is a function value of each parameter with regard to the other six parameters along with the weight assigned by the DRASTIC index (Babiker *et al.* 2005; Rahman 2008). The effective weight of each DRASTIC parameter exhibited some variation when compared with the theoretical weight (Table 5). Depth to water table (mean 26.17%) and net recharge (mean 22.27%) were the most effective parameters in the vulnerability assessment due to their higher effective weight than theoretical weight (21.74% and 17.39%, respectively). Slight variation in the effective weight was observed for topography (5.79%) when compared with theoretical weight (4.35%). In contrast, the remaining parameters exhibited higher theoretical weights rather than effective weight. Zghibi *et al.* (2016) found hydraulic conductivity and net recharge to be the most effective parameters, probably due to their higher effective weight than theoretical weight. The significance of depth to water table and net recharge layers emphasize the importance of detailed, accurate, and representative information about these factors.

DRASTIC index validation

DRASTIC is an empirical method which needs to be validated. Validation can be performed in several ways but the most reliable method is to compare the vulnerability index/map with water quality parameters (Ghazav & Ebrahim 2015). Electrical conductivity (EC) and nitrate ion (NO_3^-), which are notably more common water quality indicators (Javadi *et al.* 2011), were used to validate the vulnerability map in this study. EC represents the total amount of dissolved ions in water which are controlled by geology/rock types and presence of contaminants. Nitrate is essential to evaluate the DRASTIC index as it represents pollution input from seepage, fertilizers, industrial and household waste (Zghibi *et al.* 2016). For this purpose,

Table 5 | Theoretical and effective weights of DRASTIC parameters

			Effective weight %				
Parameters	**Theoretical weight**	**Theoretical weight %**	**Min**	**Max**	**Mean**	**SD**	**CV %**
D	5	21.74	19.88	34.48	26.17	3.24	12.39
R	4	17.39	15.73	29.41	22.27	3.08	13.83
A	3	13.04	8.24	20.93	12.79	3.10	24.26
S	2	8.70	1.15	11.42	3.44	2.306	66.96
T	1	4.35	3.14	.197	5.79	1.052	18.16
I	5	21.74	6.54	27.2	17.2	6.81	39.51
C	3	13.04	8.24	21.09	12.3	2.5	20.29

groundwater samples from 101 observation wells were collected in May 2014 and EC and NO_3^- were determined using the standard procedure (APHA 2012). Spatial distribution map of both the parameters (Figures 10(a) and 10(b)) showed a certain degree of similarity with the vulnerability map (Figure 9). EC varies from 260.1 to 9,702 $\mu S \cdot cm^{-1}$ while NO_3^- ranged from 0.23 to 21 mg/L. Both parameters exhibited high concentration in the southern coastal very high vulnerable zone which adjoins the Arabian Sea. Contrary to EC which showed higher concentration in the central Sindh region (Nausheroferoz, Larkana, and Nawabshah), NO_3^- concentration was high in northern Sindh (Jacobabad) which is a highly vulnerable zone on the DRASTIC map.

To further verify the relationship of the vulnerability index with EC and NO_3^-, Pearson's correlation analysis was performed (Table 6). The vulnerability index illustrated significant correlation with both EC and NO_3^- concentration

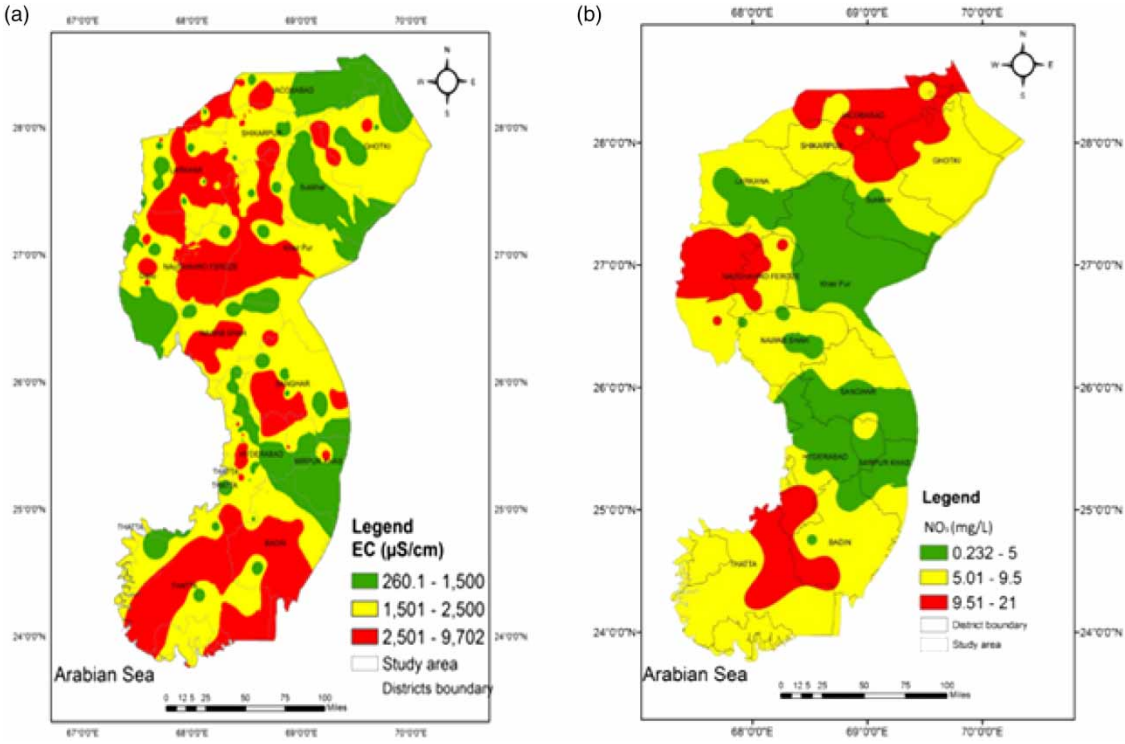

Figure 10 | Water quality map for DRASTIC validation: (a) EC map and (b) NO_3^- map.

Table 6 | Correlation between DRASTIC final results and water quality parameter (EC and NO_3^-) for DRASTIC index validation

Correlations

		Vulnerability index	EC	NO_3^-
Vulnerability index	Pearson correlation	1	0.270**	0.500**
	Sig. (2-tailed)		0.006	0.000
	N	101	101	101
EC	Pearson correlation	0.270**	1	0.064
	Sig. (2-tailed)	0.006		0.526
	N	101	101	101
NO3	Pearson correlation	0.500**	0.064	1
	Sig. (2-tailed)	0.000	0.526	
	N	101	101	101

**Correlation is significant at the 0.01 level (2-tailed).

($p \leq 0.01$) but non-significant correlation was observed between EC and NO_3^- ($p \leq 0.01$). This allowed the conclusion that high and low vulnerable zones in the vulnerability map are the potential zones of high and low contamination, and high nitrate concentration is the consequence of the input from agricultural fertilizers, industrial and domestic sewage contamination in Sindh province. The higher EC was the resultant output of water logging and salinity, seawater intrusion from the Arabian Sea, aquifer geology, and other anthropogenic activities rendering the groundwater of the lower Indus Plain more vulnerable to contamination. Mahessar *et al.* (2017) found that 78% of groundwater quality in Sindh province is saline and brackish. The indiscriminate effluents from industrial municipal wastewater along with fertilizers and pesticides in agricultural fields eventually leach into the groundwater resulting in contaminated pools and altering the quality of groundwater.

CONCLUSION

In this study, the DRASTIC method was used to evaluate the vulnerability of the lower Indus aquifer to contamination, and the map was classified into three zones, medium, high, and very high vulnerable zones. The very high vulnerable zone covering 28.03% of the area is distributed in Jacobabad and the lower Sindh southernmost coastal area. 56.76% of the total area is highly vulnerable to contamination, and is distributed in the central Sindh region while 15.21% is in the medium vulnerable zone. Nevertheless, no area was free from contamination risk based on the DRASTIC index value. Sensitivity analysis revealed that depth to water table and net recharge are the most effective parameters responsible for highest variation in the vulnerability index. Two water quality parameters, EC and NO_3^- maps, were used to validate the DRASTIC method, which coincides with the vulnerability map and illustrated a significant correlation with the vulnerability index. This study suggests that DRASTIC is a useful tool for groundwater vulnerability assessment and can prioritize susceptible areas. Conclusively, proper planning is required to solve the drainage problem in the whole study area to avoid further contamination of the groundwater resource.

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