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Study of GIS-based groundwater potential zones for agricultural sustainability in the arid region

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ABSTRACT

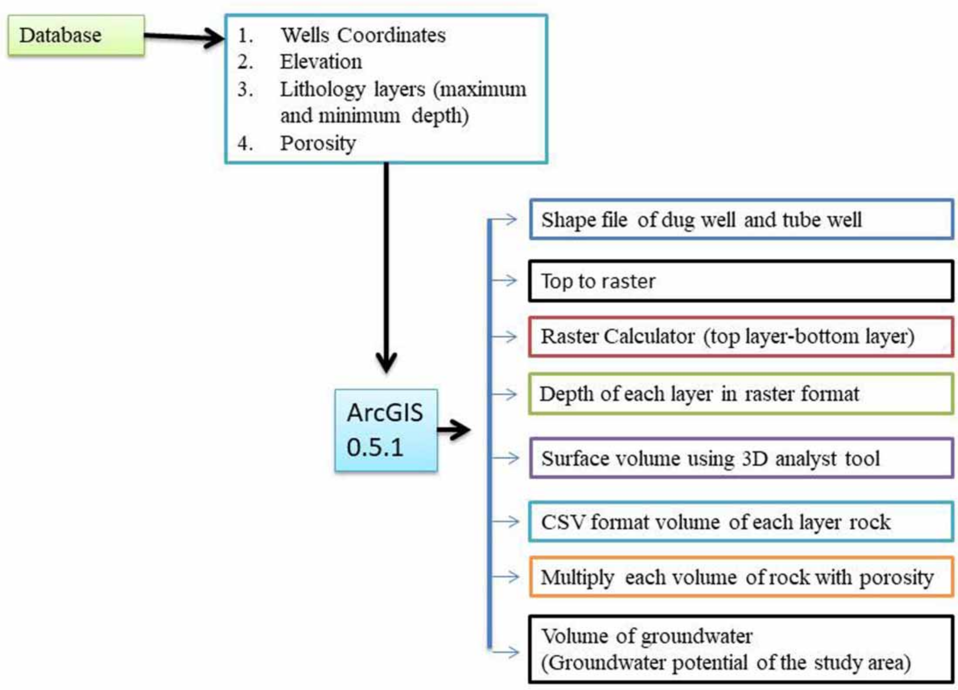
The cluster-wise area of shallow and deep aquifer zones is used to estimate the potential of groundwater. The potential of the shallow aquifer zone is estimated at 4.61 MCM (million cubic meters) and for the deep aquifer zone at 17,509.03 MCM, while the total groundwater potential for both aquifer zones is estimated at 17,513.64 MCM. The Geographical Information System (GIS) was employed efficiently to estimate the subsurface volume of the lithological rock layers using cost-effective and time-saving techniques, while the Rockwork software integrated with GIS was successfully used to visualize the subsurface lithology and stratigraphy of the aquifer zones. The estimated potential of groundwater can be uncovered by using the alternative solar pumping system to improve the agricultural system in the study area, thereby reducing the migration rate, reducing poverty, and improving the socio-economic conditions of livelihood. In the future, too, it will be essential to design water quality studies to ensure the proper use of groundwater.

Key words: aquifer zone, deep and shallow, groundwater potential, lithology, stratigraphy

HIGHLIGHTS

- The current study discovered two potential groundwater zones of the (shallow and deep) aquifer.
- The potential of the groundwater has been estimated using GIS for future planning and development.
- The overall groundwater potential for both aquifer zones is estimated at 17,513.64 MCM.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Agriculture is the backbone of the economy of any country and freshwater resources are essential drivers for sustainable development, especially in the world's dry regions. In contrast, the accessibility of groundwater (GW) is limited and depends on the precipitation pattern in arid regions. Increasing the population leads to water demand for food and fiber (Singh 2019).

Consequently, the domestic, agricultural, and industrial sectors increase utilization and decrease resources. In light of the above statement, GW resources are under threat globally (Varua *et al.* 2018; Kalhor *et al.* 2019; Singh 2019; Singh *et al.* 2019). Converting agricultural lands into dry regions is due to the quick declination of surface and GW reservoirs (Gaaloul 2014).

GW is suitable for freshwater resources and easy to extract for utilization (Panhwar *et al.* 2022; Solangi *et al.* 2022a). The quality and quantity of the GW resources vary from region to region and with their lithology. Some areas have assessed freshwater through shallow aquifers and some have done vice versa through a deep aquifer (Singh 2015). Pakistan is one of the most water-challenging countries globally and depends on the arid to semi-arid climatic region (Keerio *et al.* 2020). GW is one of the most valuable natural resources of drinking water (Nassiri & Mehdinejad 2022; Uc Castillo *et al.* 2022), supportive of human health and economic growth. MacAllister *et al.* (2022) studied regional post-monsoon GW accumulation at a regional scale from 1900 to 2010. They showed that Pakistan has historically enormous GW potential. The availability of GW gradually increased to 3.6 cm/year in the early 20th century due to the development of an extensive irrigation canal network that increased the yield of GW formation. While the status of the GW level was stable between 1970 and 2000 due to above and average rainfall and tubewell development for irrigation. Later, in the first decade of the 21st century, GW yield began to decrease by 2.8 cm/year due to erratic precipitation patterns and tube well development. Pakistan ranks fourth in the world for GW abstraction countries; that extract 65 BCM (billion cubic meters) annually and have 55 BCM of sustainable GW resources. (Alam *et al.* 2022). Currently, the GW availability is below 1,000 m^3/per capita annually, which is expected to reduce up to 837 m^3/per capita by December 2025 (Engelman & LeRoy 1993). Consequently, a precise assessment of GW potential is vital because water resources are serious to economic development in these areas (Leketa *et al.* 2019).

The RS (Remote Sensing) and Geographical Information System (GIS) techniques have been important to estimate the GW potential since the mid-1990s (Jasrotia *et al.* 2013; Solangi *et al.* 2022b). The integrating approach of the RS/GIS overcomes the most critical problems and provides quick information on broader utilization

(Rather *et al.* 2022), a time-saving and cost-benefit practice, with applicable processing results through productive outcomes. A GIS method might be applied efficiently to associate unexpected hydrogeological themes observed in the GW perspective on a particular regional scale (Shahid *et al.* 2000), it is also a convenient method to identify the GW potential (Ombasa *et al.* 2022). RS and GIS are the leading systems for the ecological growth of essential GW resources, primarily in countries with a deficiency of data. In previous surveys, the depiction of GW potential has been researched by utilizing GIS innovation with lithological layer data. Evaluated the GW potential creating different layers of each stone and the information on porosity has been interpreted with the thickness of each rock layer (Shahid *et al.* 2000). However, it is essential to determine the potential of GW resources to combat the challenging situations of the increasing population and climate change vulnerabilities. The current study is aimed to assess the potential GW zones for agricultural sustainability in the remote area of district Dadu Sindh, Pakistan. Some basic information about the proposed study area is as follows:

1.1. Climate

The study area is climatically arid in the semi-arid region and depends on precipitation as a primary source. The average annual rainfall is about 120 mm, while the monsoon falls from July–September.

The study area experienced several devastating floods and droughts over the past 81 years (1933–2013). Droughts and floods have been extensive in the current periods. The recent drought from 1996 to 2002 severely affected the study area, reducing water resources, water table levels and water quality and increasing mortality rates, migration rates, and poverty (Soomro A. *et al.*, 2019; Bisharat 2016). In 2010, significant flooding occurred in the study area, increasing the death toll, causing land degradation, destroying infrastructure, devastating the agricultural system, and damaging shallow wells (Soomro, A. *et al.* 2019; Soomro *et al.* 2019a, 2019b). In the normal precipitation cycle, the runoff is diverted to the arid lands for farming practices, subsequently, GW is used to supplement irrigation and livelihood practices. The study area falls in climatically arid to semi-arid regions. The hottest month is June with a temperature of about 45 °C and the coldest month is January where the temperature varies below 14 °C.

1.2. Agriculture

Agriculture is the backbone for sustainable development in the study area. Rabi and Kharif are two cropping seasons in the study area that depend on the GW resources. The primary precipitation months are the monsoon from July to September each year. The rest of the year's agriculture and livelihood activities depend on the precipitation and GW resource. Precipitation creates runoff which is diverted by the local people for the agricultural purpose. Soomro *et al.* (2020) researched the same area using RS and a hydrological modeling approach. They showed that 86.25% of the settlements in the study area, followed by 83.85% of the land, used runoff water for agricultural purposes. Likewise, 65% of the area was used for agriculture. Due to the elevation compared to the Indus River, farmers have captured 39.50% of the runoff in the farmland and ditches in the form of wetlands. Consequently, the stored water is used for supplemental irrigation and replenishment of the shallow aquifer. Cotton, wheat, cluster beans, pulses, sesame, and vegetables are the major crops in the study area. During the drought seasons, local people migrate to the agricultural and industrial regions and return during the wet seasons. In this situation, the sustainability and planning of the GW may play a vital role in sustainable development in the region.

1.3. Hydrology

The study area consists of a hilly tract and most of the settlements are situated in the foothills. Rainfall is the main source of torrential runoff. Most of the floods are generated in hilly areas that move to the foothill area and collect fresh floods. To reduce the velocity of the floods, the farmers divert one-third quantity of the floods to their agricultural lands by raising periphery bunds around the lands, and the rest of the runoff wastes into the Arabian Sea through the Indus River without use. In the study area, the floods are collected in the natural depression ponds, manmade constructed ponds/reservoirs, and periphery bunds (Varua *et al.* 2018). The torrential runoff spreads in the study area through numerous sub-torrents. The 'Nai Gaj' is the mighty torrential source of runoff and other average torrents Mirani, Naing, and Angai Nai are prominent in the study area.

1.4. Groundwater

The study area depends on two aquifer zones, i.e. shallow (dug wells) and deep (tube wells) aquifers. The primary source for recharging aquifers is precipitation. The GW is extracted for agriculture and livelihood cores (Frenken 2012). The GW level fluctuates with seasonal variations.

1.5. Rock formation

The lithological survey area includes the Khirthar formation area (Figure 1). The formation consists of alluvial soil, gravel, clay, sand, and limestone, as collected from drill log lithology, etc. The excess amount of sand, silt, as clay deposited in the flood plains is called, alluvial soil. Mostly identified in the river springs. They can also be found in the higher areas of the floodplains. It is the first upper layer below the surface of the earth with fairly deposited nutrient levels (Hakeem *et al.* 2014). The Gaj Formation includes limestone, sandstone, shale, and light aggregates. In the middle Miocene-age, a large part of the freshwater aquifer closed the mountain streams, mostly at shallow depths (Soomro *et al.* 2022).

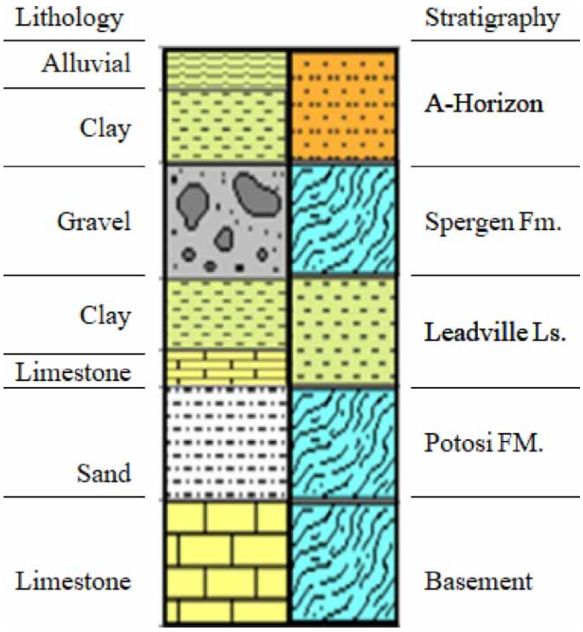


Figure 1 | Khirthar formation.

2. MATERIALS AND METHODS

2.1. Study area

The study area is situated in the hilly southwestern portion of the lower Indus River, covering an area of 1,442.13 km^2 of district Dadu, Sindh, Pakistan, and lies between longitudes from 67.167735'E to 67.682658 (dd)'E and latitudes from 26.136681'N to 26.593051 (dd)'N with uneven topography (Figure 2). The study area is well known as the 'KAACHO,' one of the leading dry regions and rich in flora and fauna. The study area is administratively divided into various small union councils with a population of 250,339.

2.2. Data collection

The data on GW extraction, daily pumping, seasonal basis pumping, and land use cover under various cropping patterns have been collected using the questionnaires filled out by the stakeholder through interviews. The 14 deep wells and four dug wells data have been collected (Figure 2). The hydraulic data of GW sources were measured through the measuring tape and monitored from October 2016 to April 2019, the aquifer level was on a seasonal basis for the dry and wet seasons to monitor how the regional climate affects the GW aquifer. The coordinates of all the GW resources have been recorded through the GPS (Global Positioning System) and confirmed by Google Earth Pro. ArcGIS was employed to change point shapefiles into KML format. The database has been recorded in Table 1. The lithological information regarding the study area has been collected

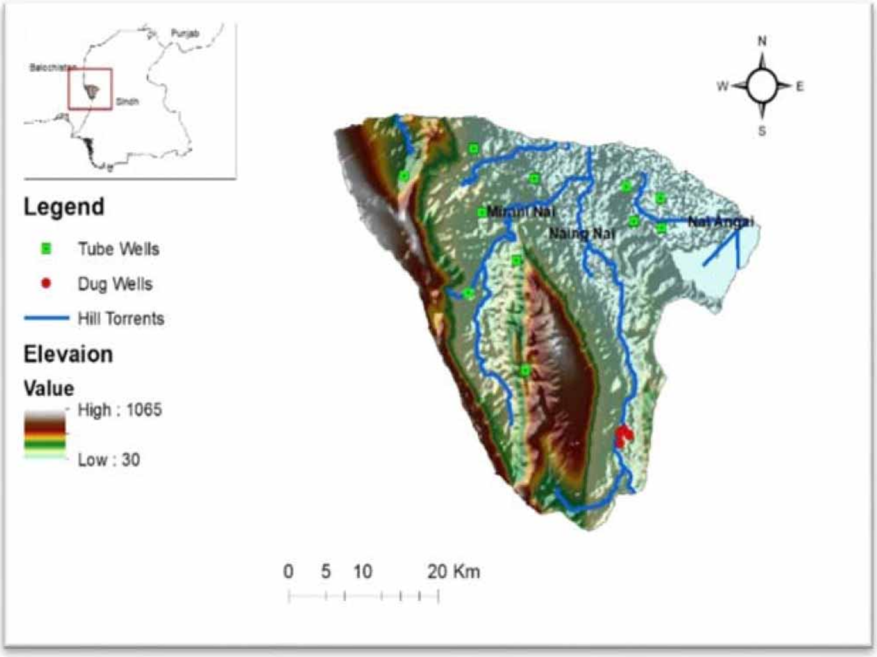


Figure 2 | Layout map of the study area and locations of existing groundwater.

through the literature citation, collected through the revenue, irrigation, and soil survey departments. The lithological logs of the GW resources have been received from the Mining and Industrial Consultants, who worked on the installation of a dug well and a deep well in 1990 for a project under the Government of Sindh.

2.3. Estimation of rock volume using GIS application

The dataset has been developed into an Excel sheet and converted into a CSV (Comma-Separated Values) format. The bore log data has been used to visualize the actual underground situation of the rock layers employing the Rockwork 15 version. The lithology setup was converted into the stratigraphy and developed in the 3D (Three-Dimensional) thematic map to represent the rock layers (Figure 3) of the GW resources in the study area. The database of bore logs for each dug well and deep well has been shown through coordinate systems in ArcGIS version 10.5.1 and developed the thematic layers of the deep and shallow aquifers. Each thickness of lithology is converted into a volume using the raster calculator in GIS and the porosity data of the layer is multiplied by volume to estimate the specific yield GW potential. The highlighted portions of Table 2 (Khokhar *et al.* 2016) indicated the porosity values used to convert into water potential for the particular layers. The detailed methodology is described in Figure 4.

3. RESULTS AND DISCUSSION

3.1. Visualization of lithology and stratigraphy

Figure 4 shows the detailed visualization and investigation of both shallow and deep aquifer zones in 3D views. The 3D survey identified the structures of the subsurface soil layer and the spatial distribution of the existing GW resources in both clusters, with the visualization showing the extent of the aquifers and the soil layers in different colors (Figure 5).

3.2. GW potential district Dadu

Table 3 shows that the study area covers 1,442.13 km^2, while the cluster area of shallow aquifer zone 2.65 km^2 and deep aquifer zone 1,008.28 km^2 covers the study area. The four dug wells in the shallow aquifer zone and 14 tube wells in the deep aquifer zone were selected and monitored for study purposes. A limited area under a dug well has been chosen due to some limitations of the hilly mountainous region and its physiographic conditions. The total area of 1,010.93 km^2 was monitored under both clusters of aquifer zones.

Table 1 | Database of tube wells and dug wells information and water levels in the study area

No.	Name of farmer	Well ID	Elevation (m)	Min. level (m)	Max. level (m)	Base of well (m)	Longitude	Latitude	The total depth of well (m)
1	Moosa Khan Baazmaad Village, Johi	DTW 1	51	23.80	22.10	−71.00	67.50645	26.74077	122
2	Aashiq Ali khoso, Johi	DTW 2	45	26.80	26.40	−46.50	67.52888	26.7322	91.5
3	Mohammad Moosa Leghari, Wahi Paandhi	DTW 3	54	−13.87	−14.22	−83.20	67.36399	26.65488	137.2
4	Ghulam Asghar Leghari	DTW 4	55	−15.12	−16.09	−67.00	67.36392	26.64442	122
5	Pyar Ali Rustmani	DTW 5	55	−15.01	−16.08	−67.00	67.52666	26.64422	122
6	Bhoora Khan Rustmani,Wahi Pandhi	DTW 6	55	14.5	13.45	−51.4	67.36246	26.65466	109.4
7	Abdul Aziz Rustmani, Wahi Paandhi	DTW 7	53	3.9	3.1	−103.4	67.40432	26.65701	152.4
8	Zulfiqar Ali Rustmani, Wahi Pandhi	DTW 8	49	3.92	3.01	−103.4	67.40422	26.65711	152.4
9	Deedar Ali Rustmani, Gaj Nai	DTW 9	49	5.92	4.91	−104.4	67.41022	26.65802	152.4
10	Raees Ali Ghulam Leghari, Near Gaj Nai	DTW 10	50	7.91	6.78	−69	67.36343	26.65905	122
11	Jhangar Bajara, Dadu	DTW 11	50	40.5	38.8	−41.5	67.57109	26.308899	91.5
12	Bajara, Dadu	DTW 12	46	36.8	35.8	−45.5	67.572269	26.308351	91.5
13	Bajara, Dadu	DTW 13	46	36.95	36.2	−60.8	67.5743	26.308121	106.8
14	Jhangar Bajara, Dadu	DTW 14	49	37.8	36.5	−73	67.577608	26.309821	122
15	Jhagara Bajara, Dadu	DDW 1	45	40.08	39.75	5.5	67.516881	26.230153	39.5
16	Jhagara Bajara, Dadu	DDW 2	49	39.5	37.91	3.27	67.513276	26.23187	45.73
17	Jhagara Bajara. Dadu	DDW 3	50	40.75	40.35	11.5	67.515293	26.23579	38.5
18	Bajara, Dadu	DDW 4	49	39.35	38.5	18.52	67.525456	26.249538	30.48

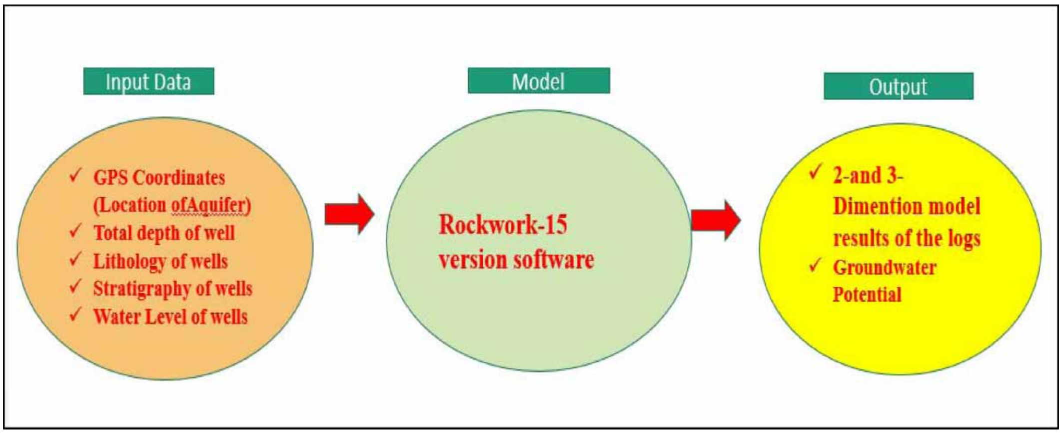


Figure 3 | Flowchart of elaborating the visualization procedure of lithology and stratigraphic of the wells in 3D using Rockwork 15.

Table 2 | Lithological formation and its porosity in the study area

The porosity of the soil layer

Lithology	Porosity (%)	Porosity
Alluvial	30.2	0.30
Silt	53.2	0.53
Sand	30.0	0.30
Gravel	40.0	0.40
Clay	42.4	0.42
Shale	17.0	0.17
Limestone	15.0	0.15

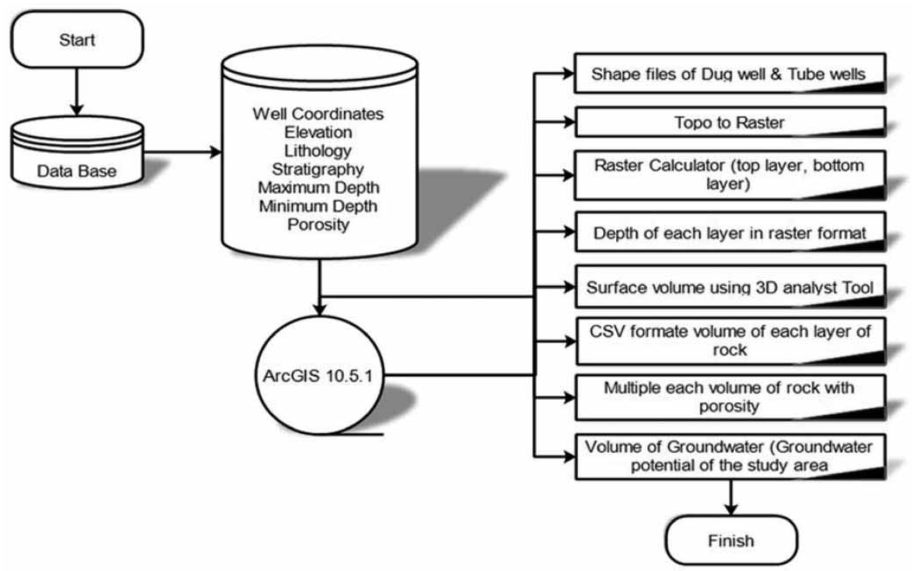


Figure 4 | Flowchart of methodology.

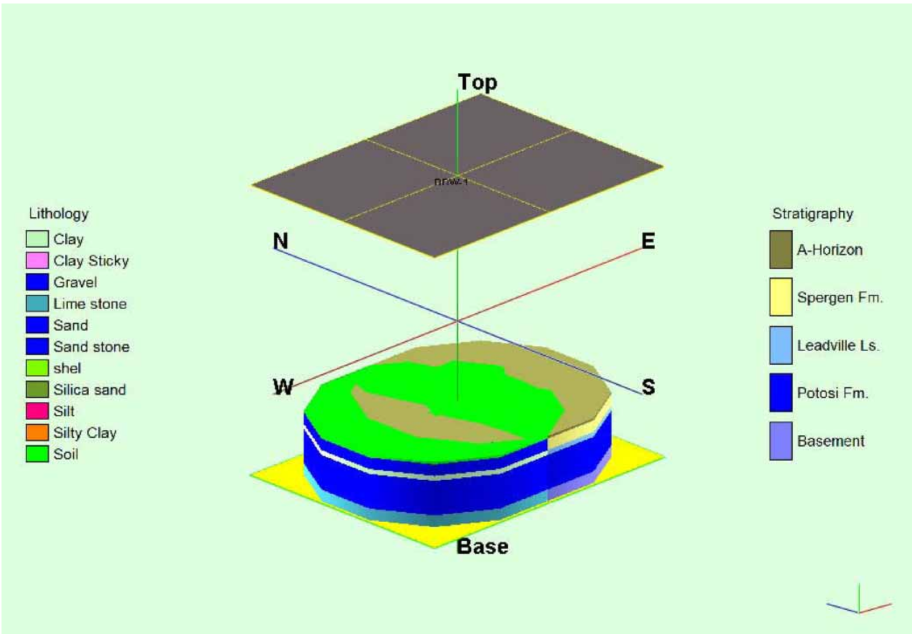


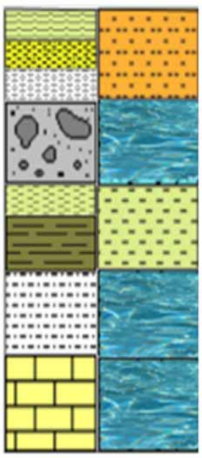
Figure 5 | Rockwork 3D model visualization of lithology and stratigraphy.

Table 3 | The area under different aquifer zones

District	Study area (km^2)	Aquifer zone	Number of wells	Cluster-wise area (km^2)
Dadu	1,442.13	Shallow	04	2.65
		Deep	14	1,008.28
Total			18	1,010.93

Table 4 depicts the GW potential of the shallow aquifer (dug wells) zone in the study area. Table 4 represents two parts of the figure and tabular formations. The figure formation showed sub-divided portions of the subsurface lithology and straitigraphical rock layer representations of shallow aquifers. The table discloses that the slice of A-Horizon containing the soil layers of alluvial, silt, and sand consists of the volumetric capacity of rock 6,186,266.20 m^3. Spergen Fm has a rock layer of gravel with a volume of 7,089,070.00 m^3. Leadville Ls leads the soil layer of clay and shale with a volume of 4,363,068.30 m^3. Potosi Fm is rich with sand soil containing a volume of 4,707,350.87 m^3 and the basement is full of limestone rock with 2,428,706.98 m^3. The lithological rock layers of gravel, sand, and limestone contain a porosity of 0.4, 0.3, and 0.15% and the potential of GW is 2.84, 1.41, and 0.36 MCM (million cubic meters), respectively. The total GW potential is estimated at 4.61 MCM in the shallow aquifer zone.

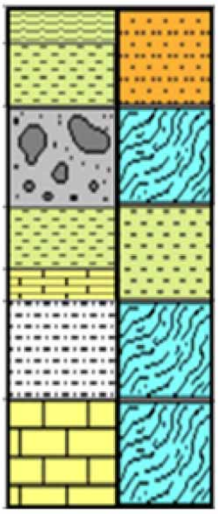
Table 4 | Cluster-wise GW of a dug well in the Khirthar formation of the district Dadu



Lithology	Stratigraphy	Elevation (m)	Volume of Rock (MCM)	Porosity	Vlume of Water (MCM)
Alluvial Silt Sand	A-Horizon	49.00 43.50	6.18	0.00	0.00
Gravel	Spergen Fm.	43.50 33.50	7.08	0.40	2.84
Clay Shlale	Leadville Ls.	33.50 31.50	4.36	0.00	0.00
Sand	Potosi FM.	31.50 10.50	4.707	0.30	1.41
Limestone	Basement	10.50 3.27	2.42	0.15	0.36
				Groundwater Potential	4.61

Table 5 portrays the GW potential of the deep aquifer (tube wells) zone. The table is sub-divided into figural and tabular portions. The lithology and straitigraphical layers disclosed that the slice of A-Horizon contains alluvial and clay soil layers and occupies the rock volume of 26,040,684,328.58 m^3. Spurgeon Fm covered only the rock layer of gravel with a volume of 18,176,894,977.77 m^3, having a porosity of 0.4% and estimated the potential of GW at 7,270.76 MCM. Leadville Ls clay contains a limestone rock layer with a volume of 10,330,789,857.39 m^3. Potosi Fm includes a sand layer volume of 27,488,333,542 m^3, having 0.30% of porosity and a potential for GW of 8,246.50 MCM. The basement cover layer of limestone with a volume of 13,278,503,609.64 m^3, having 0.15% of the porosity the potential of GW 1,991.78 MCM, however the total GW potential in the deep aquifer zone has an estimated 17,509.03 MCM. Though, the clusters of both aquifer zones (shallow and deep) in the study area, determined 17,513.64 MCM.

Table 5 | Cluster-wise GW of a tube well in the Khirthar formation of the district Dadu



Lithology	Stratigraphy	Elevation (m)	Volume of Rock (MCM)	Porosity	Vlume of Water (MCM)
Alluvial Clay	A-Horizon	49.00 37.10	2604.06	0.00	0.00
Gravel	Spergen Fm.	37.10 -13.50	18176.89	0.40	7270.76
Clay Limestone	Leadville Ls.	-13.50 -21.50	10,330.78	0.00	0.00
Sand	Potosi FM.	-21.50 -91.50	27,488.33	0.30	8246.50
Limestone	Basement	-91.50 -103.40	13,278.50	0.15	1991.78
			Groundwater Potential		17509.03

The alluvial and the upper layer of soil: just below the surface contain the surficial deposition of the rock layer, which has porosity but does not contribute to the groundwater. The other soil layers shale, clay, and silt react as aquitards that restrict the flow of GW because of squat penetrability, that is not measured for potential GW zone (soil quality).

3.3. Regional agriculture sustainability

The current agricultural scenario is unsustainable due to negative impacts on natural resources and the global environment. About one-third of agricultural land has been degraded by waterlogging, salts are affected, up to 75% of cultural genetic diversity has been lost through the replacement of hybrid seed, 22% of animal breeds are endangered, about 13 million hectares of forest have been converted to other land uses every year. Most of the agricultural land is urbanized due to the high-income yield. The sustainability of agriculture is the greatest challenge facing humanity worldwide. The gradually growing population of 9.0 billion people needs food security and will demand 60% more basic foodstuffs by 2050. At the same time, around 793 million people worldwide suffer from hunger, as reported by Ursu & Petre (2022).

To meet these challenges, it is important to protect the existing natural resources, which could be used with smart techniques at the regional scale to conserve the natural resources and agricultural system to improve food security (Laurett *et al.* 2021). The results of sustainable agriculture are reflected in sustainable production – ecological, economical, and social. Likewise, the exposed GW potential can be used sensibly for sustainable agriculture with innovative techniques, which improves the socio-economic conditions at the regional level of the study area.

4. CONCLUSION

The study has conducted cores in the arid mountainous region of the Dadu district depending on rainfall as the main source of agriculture and livelihood. The study area has historical experience with massive flooding and prolonged periods of drought. The GW source is often used in the study area to cover the food and fiber requirements. The current scenario of GW resources is severe in the study area. The current study identified two shallow and deep aquifer zones consisting of the Khirthar formation in the study area. The lithological soil strata contain potential aquifers in the gravel, sand, and limestone and allow for lithological and stratigraphically visualized analysis and investigation through the 3D view. The present study has estimated the total GW potential for the Dadu district for a dense cluster of shallow and deep zones. GW potential results include 4.61 and 17,509.03 MCM, respectively. Total GW potential was estimated at 17,513.64 MCM in shallow and deep clusters of the study area. The GIS was used to determine GW potential and a reliable data set for numerical GW modeling, integration, demonstration of image processing, and modeling results was developed. The current study supported GIS and Rockwork, which helped achieve the goals of the current GW potential reviews.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Alam, F., Azmat, M., Zarin, R., Ahmad, S., Raziq, A., Young, H. W. V., Nguyen, K. A. & Liou, Y. A. 2022 Identification of potential natural aquifer recharge sites in Islamabad, Pakistan, by integrating GIS and RS techniques. *Remote Sensing* **14**(23), 6051.

Bisharat, M. 2016 Indus Basin Drought (1999–2000) Impact on irrigated agriculture – A policy review in the preview of Mega Storages and Floods. In: *2nd World Irrigation Forum*, 6–8 November 2016, Chiang Mai, Thailand. W.1.1.17.

Engelman, R. & LeRoy, P. 1993 Sustaining water: Population and the future of renewable water supplies.

Frenken, K. 2012 Irrigation in southern and Eastern Asia in figures: aQUASTAT survey-2011. *Water Reports* **37**.

Gaaloul, N. 2014 GIS-based numerical modeling of aquifer recharge and saltwater intrusion in arid southeastern Tunisia. *Journal of Hydrologic Engineering* **19**(4), 777–789.

Hakeem, K., Sabir, M., Ozturk, M. & Mermut, A. 2014 Soil remediation and plants: prospects and challenges.

Jasrotia, A. S., Bhagat, B. D., Kumar, A. & Kumar, R. 2013 Remote sensing and GIS approach for delineation of groundwater potential and groundwater quality zones of Western Doon Valley, Uttarakhand, India. *Journal of the Indian Society of Remote Sensing* **41**(2), 365–377.

Kalhor, K., Ghasemizadeh, R., Rajic, L. & Alshawabkeh, A. 2019 Assessment of groundwater quality and remediation in karst aquifers: a review. *Groundwater for Sustainable Development* **8**, 104–121.

Keerio, H. A., Panhwar, S., Shah, S. A., Naji, A. M., Ali, A. & Aftab, A. 2020 Investigation of climate change variability under climate change conditions over the semi-arid region. *Journal of Mechanics of Continua and Mathematical Sciences* **15**, 46–54.

Khokhar, Q. D., Hakro, A. A. A. D., Solangi, S. H., Siddiqui, I. & Abbasi, S. A. 2016 Textural evaluation of nari formation, Laki Range, Southern Indus Basin, Pakistan. *Sindh University Research Journal-SURJ (Science Series)* **48**(3), 1–6.

Ombasa, D. T., Kosgei, J. R., Nyandwaro, G. & Munishi, E. S. 2022 Multi-criteria approach to assess groundwater potential: a case study of Baringo County, Kenya. *Water Practice and Technology* **17**(10), 2199–2223.

Laurett, R., Paco, A. & Mainardes, E. W. 2021 Measuring sustainable development, its antecedents, barriers and consequences in agriculture: an exploratory factor analysis. *Environmental Development* **37**, 100583.

Leketa, K., Abiye, T., Zondi, S. & Butler, M. 2019 Assessing groundwater recharge in crystalline and karstic aquifers of the Upper Crocodile River Basin, Johannesburg, South Africa. *Groundwater for Sustainable Development* **8**, 31–40.

MacAllister, D. J., Krishan, G., Basharat, M., Cuba, D. & MacDonald, A. M. 2022 A century of groundwater accumulation in Pakistan and Northwest India. *Nature Geoscience* **15**(5), 390–396.

Nassiri, M. & Mehdinejad, M. H. 2022 Groundwater quality assessment of north of Iran (Golestan Province) using multivariate factor analysis and GIS techniques. *Water Practice and Technology* **17**(6), 1284–1293.

Panhwar, M. Y., Panhwar, S., Keerio, H. A., Khokhar, N. H., Shah, S. A. & Pathan, N. 2022 Water quality analysis of old and new Phuleli Canal for irrigation purpose in the vicinity of Hyderabad, Pakistan. *Water Practice & Technology* **17**(2), 529–536.

Rather, A. F., Ahmed, R., Wani, G. F., Ahmad, S. T., Dar, T., Javaid, S. & Ahmed, P. 2022 Mapping of groundwater potential zones in Pohru Watershed of Jhelum Basin-Western Himalaya, India using integrated approach of remote sensing, GIS and AHP. *Earth Science Informatics* **15**(4), 2091–2107.

Shahid, S., Nath, S. & Roy, J. 2000 Groundwater potential modelling in a soft rock area using a GIS. *International Journal of Remote Sensing* **21**(9), 1919–1924.

Singh, A. 2015 Soil salinization and waterlogging: a threat to environment and agricultural sustainability. *Ecological Indicators* **57**, 128–130.

Singh, A. 2019 Environmental problems of salinization and poor drainage in irrigated areas: management through the mathematical models. *Journal of Cleaner Production* **206**, 572–579.

Singh, A., Panda, S. N., Uzokwe, V. N. & Krause, P. 2019 An assessment of groundwater recharge estimation techniques for sustainable resource management. *Groundwater for Sustainable Development* **9**, 100218.

Solangi, G. S., Siyal, A. A., Siyal, Z. U. A., Siyal, P., Panhwar, S., Keerio, H. A. & Bhatti, N. B. 2022a Social and ecological climate change vulnerability assessment in the Indus delta, Pakistan. *Water Practice & Technology* **17**(8), 1666–1678.

Solangi, G. S., Shah, S. A., Alharbi, R. S., Panhwar, S., Keerio, H. A., Kim, T. W., Memon, J. A. & Bughio, A. D. 2022b Investigation of irrigation water requirements for major crops using CROPWAT model based on climate data. *Water* **14**(16), 2578.

Soomro, A., Qureshi, A. L., Jamali, M. A. & Ashraf, A. 2019 Groundwater investigation through vertical electrical sounding at hilly area from Nooriabad toward Karachi. *Acta Geophysica* **67**(1), 247–261.

Soomro, A. G., Babar, M. M., Memon, A. H., Zaidi, A. Z., Ashraf, A. & Lund, J. 2019a Sensitivity of direct runoff to curve number using the SCS-CN method. *Civil Engineering Journal* **5**, 2738–2746.

Soomro, A. G., Babar, M. M., Ashraf, A. & Memon, A. 2019b The relationship between precipitation and elevation of the watershed in the Khirthar National Range. *Mehran University Research Journal of Engineering & Technology* **38**(4), 1067–1076.

Soomro, A. G., Babar, M. M., Arshad, M., Memon, A., Naeem, B. & Ashraf, A. 2020 Spatiotemporal variability in spate irrigation systems in Khirthar National Range, Sindh, Pakistan (case study). *Acta Geophysica* **68**, 219–228.

Soomro, A. G., Shah, S. A., Memon, A. H., Alharabi, R. S., Memon, D., Panhwar, S. & Keerio, H. A. 2022 Cascade reservoirs: an exploration of spatial runoff storage sites for water harvesting and mitigation of climate change impacts, using an integrated approach of GIS and hydrological modeling. *Sustainability* **14**(20), 13538.

Uc Castillo, J. L., Martínez Cruz, D. A., Ramos Leal, J. A., Tuxpan Vargas, J., Rodríguez Tapia, S. A. & Marín Celestino, A. E. 2022 Delineation of groundwater potential zones (GWPZs) in a semi-arid basin through remote sensing, GIS, and AHP approaches. *Water* **14**(13), 2138.

Ursu, A. & Petre, I. L. 2022 Forecasting the optimal sustainable development of the Romanian ecological agriculture. *Sustainability* **14**(21), 14192.

Varua, M. E., Ward, J., Maheshwari, B., Dave, S. & Kookana, R. 2018 Groundwater management and gender inequalities: the case of two watersheds in rural India. *Groundwater for Sustainable Development* **6**, 93–100.

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