Groundwater Vulnerability Assessment of Bannu Basin (Pakistan): Attaining United Nation Sustainable Development Goal (SDG 6)

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Abstract

Groundwater serves as a primary source of drinking and irrigation water in the Bannu Basin, making its protection from pollution a critical concern. This study aims to apply the DRASTIC model, integrated with GIS, to evaluate groundwater vulnerability in the basin. The model considers seven hydrogeological parameters to generate a spatial vulnerability map, which was further validated through nitrate concentration data. Each influencing parameter was weighted on a scale of 1 to 5, with 5 indicating the most critical contamination risk and 1 the least significant. Each sub-parameter was assessed on a scale of 1 to 10 based on its impact on pollution concentration, with higher values indicating more potential for pollution. Finally, all thematic layers were integrated in ArcGIS 10.8 to generate a vulnerability map, which is reclassified into four categories: very low, low, moderate, and high. Very low vulnerability zones, covering 476.72 km² (10.93% of the basin), are concentrated in the central basin. The most significant portion of the basin, 2034.56 km² (46.66%), falls under the low vulnerability class, indicating limited susceptibility to contamination. The moderate zone covers 1593.41 km² (36.54%), while the high-vulnerability zones are relatively small, occupying 255.63 km² (5.86%) of the basin, typically where coarse sediments and shallow groundwater depths favour pollutant migration. Nitrate-based validation showed strong spatial concordance between elevated nitrate concentrations and high-vulnerability zones, reinforcing the model's predictive accuracy and reliability. The findings contribute to sustainable water resource management by providing decision-makers with robust tools to preserve groundwater quality, support land-use planning, and formulate targeted mitigation strategies.

Keywords: Groundwater, DRASTIC, Vulnerability, IDW, Sustainable Development.

Introduction

Among the planet's natural assets, groundwater offers a significant source of potable water. The global demand for water for irrigation, industry, and domestic use, particularly in semi-arid regions, is declining (Hussain et al., 2024). Castellazi et al. (2023) state that pervasive groundwater depletion results in a severe drop in water depth when water extraction exceeds

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aquifer recharge. Water constraints resulting from inefficient use and persistent resource mismanagement have, regrettably, remained a significant obstacle to sustainable development. In contrast to the ongoing groundwater depletion, contamination with harmful substances is causing an increasing prevalence of poor groundwater quality (Baki & Ghavami, 2023; Bera et al., 2021). According to Baki and Ghavami (2023), two significant problems with water resource management are the limited supply of groundwater and its vulnerability to contamination. The concept of groundwater vulnerability was first introduced in 1960 when Albinet & Margat (1970) defined vulnerability of an aquifer as "the possibility of hydraulic pervasion and diffusion of contaminants from ground surface into natural water table reservoirs under natural circumstances". However, the concept has steadily evolved throughout time. Groundwater vulnerability, for instance, is currently described as "the tendency and likelihood that any given contaminants reach the aquifer (Harkl, 2001).

In the past few years, water scarcity and declining freshwater quality have emerged as major problems worldwide (Hussain et al., 2024; Sresto et al., 2022). Since millions of individuals worldwide face water scarcity or lack access to clean water, preserving groundwater quality is essential to ensuring a potable water supply (Barbulescu, 2020). The World Health Organisation (WHO) reports that approximately 4 million individuals die each year from diseases caused by water, and contaminated or poor quality water poses multiple serious health concerns (Nunnelley & Smith, 2020).

There are many different sources of groundwater contamination, including both human activity and natural processes. Some of the leading causes of groundwater pollution are, however, anthropogenic, including rapid urbanisation (Ekanem et al., 2022), mining operations, inadequate sewage systems (Liggett and Talwar, 2009), intensive application of agrochemicals in agriculture (Bera et al., 2021), and inappropriate landfill sites (Han et al., 2016). Groundwater contamination monitoring is therefore necessary to determine groundwater vulnerability and implement mitigation strategies (Bera et al., 2021).

Additionally, harmful substances found in soil and rock debris can pollute groundwater (Economou & Megremi, 2021). The natural geological structure of the region further affects groundwater vulnerability by controlling water movement through the topsoil, the topsoil surface, and the subsurface (Laonamsai et al., 2023). In a broader context, groundwater vulnerability is the probability that an aquifer will become polluted due to the combined influence of natural and human interventions (Zhang et al., 2024).

Evaluating aquifer vulnerability is essential for managing and mitigating groundwater pollution. Several methods exist for determining groundwater susceptible zones, which can be systematically classified into three distinct classes: (i) the statistical approach, (ii) the process-driven simulation approach, and (iii) the overlay-based approach (Chakraborty et al., 2022; Moges et al., 2022; Nasir et al., 2021). Two factors, known as contaminants, serve as independent variables (influencing factors) in the statistical analysis, along with pollutant concentration (the dependent variable). To investigate contaminant transport, a process-driven simulation approach is established using mathematical frameworks that model groundwater pollution from an identifiable source (Chakraborty et al., 2022; Moges et al., 2022). Due to data availability issues, complex analyses, complex formulae, and limited implementation expertise, these two approaches are not commonly used to assess groundwater pollution vulnerability (Zhang et al., 2023). The most widely used technique for modelling vulnerability is the overlay-based approach. The overlay-based technique relies on hydrogeological factors that affect the flow of material that dissolves on the earth's surface into the aquifer (Nasir et al., 2021).

Different researchers have employed models developed to determine groundwater pollution. Some of the models that stand out are the following: Sensitivity Index (SI) (Atashi et al., 2023), SIGA, Decision Random Forest (DRF) (Lahjouj et al., 2020), Artificial neural networks

(ANN), Fuzzy Clustering (FC) (Javadi et al., 2020), SINTACS (Kirlas et al., 2023), AVI (Stempvoort et al., 1993), and GOD (Atashi et al., 2023). Since DRASTIC, when combined with RS and GIS, is currently considered an established method for determining groundwater susceptibility to contamination (Sivakumar et al., 2022). Therefore, the present study used the DRASTIC approach to assess groundwater susceptibility to pollution. This approach has been used by several investigators (Baki & Ghavami et al., 2023; Bera et al., 2021; Sivakumar et al., 2022).

In the northwest region of Pakistan, the Bannu Basin is a significant agricultural and urban area that depends wholly or mainly on groundwater for farming, commercial, and household use. The basin aquifer is seriously threatened by pollution from a growing population, inappropriate industrial operations, excessive pesticide use, and naturally occurring geogenic toxins, including arsenic and fluoride. The area is prone to contaminants entering the groundwater system due to its hydrogeological features, including substantial permeability and alluvial deposits (Khan et al., 2024). Furthermore, the likelihood of groundwater pollution is exacerbated by untreated wastewater and an insufficient waste management system. Evaluating groundwater vulnerability in the Bannu Basin is essential for efficient water resource management and reducing pollution. Reflecting the significance of clean, safe water for sustainable development, decision-makers can use models such as DRASTIC to identify high-vulnerability zones and implement preventive measures. To support sustainable water resource management, this research aims to offer scientific insights into groundwater vulnerability. As emphasised by the UN Sustainable Development Goals (SDGs 6), this study encourages international initiatives to combat groundwater pollution in arid and semi-arid regions.

Materials and Methods

Study Area

The study area "Bannu basin" lies in northwestern Pakistan. The Bannu basin is an intermountain basin bounded from all sides by low-elevation Mountains. The Kohat and Waziristan-Sulaiman ranges lie to the north of the basin. To the west, the basin is surrounded by the Bhittani range. To the south lie the Marwat ranges, while the Shinghar range lies to the east of the basin. The basin spatial extent between latitude 32° 20' 05' to longitude 70° 20' to 71° 10' and spanned over an area of 4360.33 km2 (Figure 1).

The basin is characterised by a semi-arid climate with low, highly variable average annual rainfall that tends to fall during the monsoon season and is occasionally augmented by winter precipitation, resulting in low natural recharge. Rainwater infiltration, canal seepage, and surface flow from nearby mountains are among the primary sources of groundwater replenishment (Rahman et al., 2018).

Quaternary alluvium predominates in the soil and superficial layers. Asymmetric hydraulic conductivity and retention attributes are produced by spatial diversity in particle size and stratification; coarse river deposits exhibit greater transmissivity compared to fine-grained interbeds (Batool et al., 2024; Biagi et al., 2020). The Gambila (Tochi) and Kurram rivers regulate surface drainage, with minor tributaries (Nalla kashu and Tarkha Algadda), canal seepage, and irrigation flow back are all significant elements of the contemporary groundwater budget (Matheswaran & Akhtar, 2023). Growing populations and intensive irrigation have led to greater withdrawal from low- and deeper-lying aquifers, posing challenges to water quality and agricultural sustainability (Bibi et al., 2023; Matheswaran & Akhtar, 2023).

Thematic map data sources and preparation

In the data-scarce Bannu Basin, the seven DRASTIC parameters were derived from field records, satellite imagery, and global datasets (Table 1). The study uses well log/strata chart data from 66 wells, acquired from the Public Health Engineering Department (PHED) divisional offices in district Bannu, Lakki Marwat, and district Karak. The majority of the parameters (A, D, I, C, and S) were derived from wells ' well logs/strata charts. These variables point measurements were subsequently interpolated (IDW) inverse distance weight employing the spatial analyst tool in ArcGIS 10.8 software in the whole basin to generate a continuous

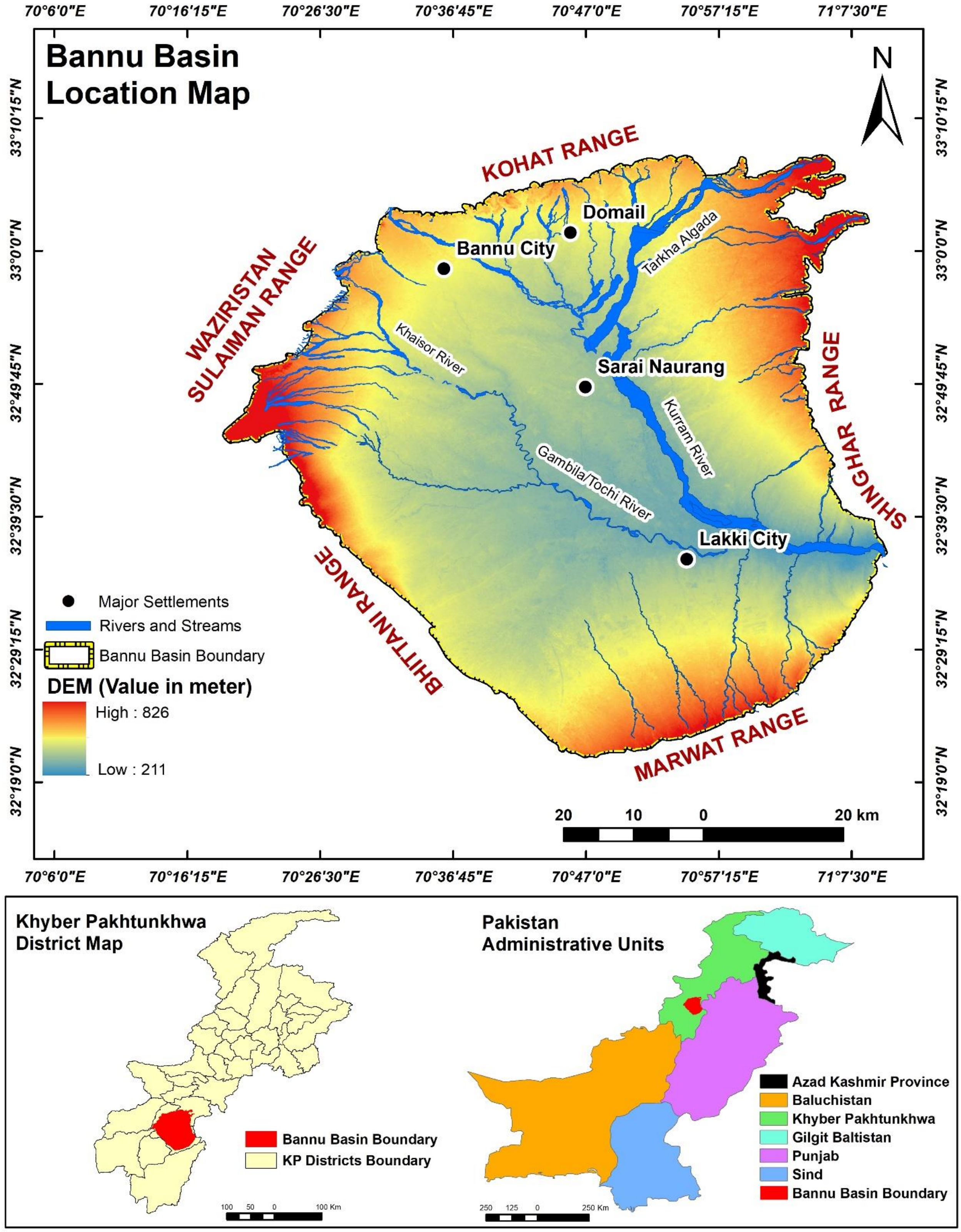


Figure 1: Illustrating Location Map

map of the water table depth (D), aquifer media (A), soil media (S), vadose zones (I), and hydraulic conductivity (C). The Bannu Basin net recharge was computed using Eq. 1 because the research region lacked accessible net recharge data (Piscopo, 2001).

Net recharge= Slope factor + Rainfall factor (mm) + Soil permeability factor…Eq. 1

Utilising the ASTER Global Digital Elevation Model (ASTER GDEM), the slope in percent was computed for the study region. The DSMW, developed by the UN-FAO, Version 3.6, was used to create the soil permeability map of the Bannu Basin. The average annual rainfall data acquired from the WorldClim global database was used to create a rainfall factor map. All three net recharge parameters were reclassified, and appropriate ranks were assigned based on the effectiveness of each sub-parameter class in the groundwater recharge. The net recharge map of the study area was computed by stacking all three-factor rank maps (Lakshminarayann et al., 2022; Piscopo, 2001). Topography (slope) (T) in percent was calculated from (ASTER GDEM-2) imagery, with 30-m resolution (Tachikawa et al., 2011). The DEM was acquired from the USGS Earth Explorer website *(http://earthexplorer.usgs.gov/*).

Table 1: Drastic Parameters data sources and mapping process

Parameters	Source	Mapping Process
Water table depth (D)	Well's logs/Strata charts. Public Health Engineering Department (PHED), Peshawar.	Interpolation
Net Recharge Capacity (R)	ASTER GDEM 2, Digital Soil Map of the World (DSMW) version 3.6(UNFAO), WorldClim, a high-resolution global climate and weather database.	Weighted sum (Piscopo et al., 2022)
Aquifer Media (A)	Well's logs/Strata charts. Public Health Engineering Department (PHED), Peshawar.	Interpolation
Soil Media (S)	Well's logs/Strata charts. Public Health Engineering Department (PHED), Peshawar.	Interpolation
Topography (Slope) (T)	ASTER GDEM 2, 30-m resolution. https://earthexplorer.usgs.gov/	Slope (GIS processing
Vadose Zones (I)	Well's logs/Strata charts. Public Health Engineering Department (PHED), Peshawar.	Interpolation
Hydraulic Conductivity (C)	Well's logs/Strata charts. Public Health Engineering Department (PHED), Peshawar.	Interpolation

Methodology

The current research utilized DRASTIC approach for vulnerability assessment. Methodology illustrated in Figure 2.

DRASTIC Model

The DRASTIC model was established by the US environmental protection agency to assess groundwater contamination risk (Aller & Thornhill, 1987). It focuses on 7 hydrogeological controlling variables; depth to groundwater table (D), recharge rate (R), aquifer media (A), soil media (S), topography (T), vadose zone impact (I), and hydraulic conductivity. ArcGIS 10.8 was used to create and integrate all seven thematic layers for aquifer vulnerability to contamination. Each influencing parameter were weighted on a scale of 1 to 5, with 5 being the most important and 1 representing the least significant contamination risk. Each sub-parameter was assessed on a scale of 1 to 10 based on its impact on pollution concentration, with higher values indicating more potential for pollution (Tufail et al., 2025; Aller & Thornhill, 1987). The weights (w) and rates (r) were multiplied to get the index value for each factor using the drastic equation 2.

$$DI = D_r D_w + R_r R_w + A_r A_w + S_r S_w + T_r T_w + I_r I_w + C_r C_w \dots\dots\dots Eq. 2$$

Where, DI is drastic index, D, R, A, S, T, I, and C are conditioning parameters, while w is conditioning parameters weight and r represent sub-parameters rate. Finally, all thematic layers were integrated using WOA in ArcGIS 10.8 model builder to generate a vulnerability map, which is reclassified into four categories: very low, low, moderate, high.

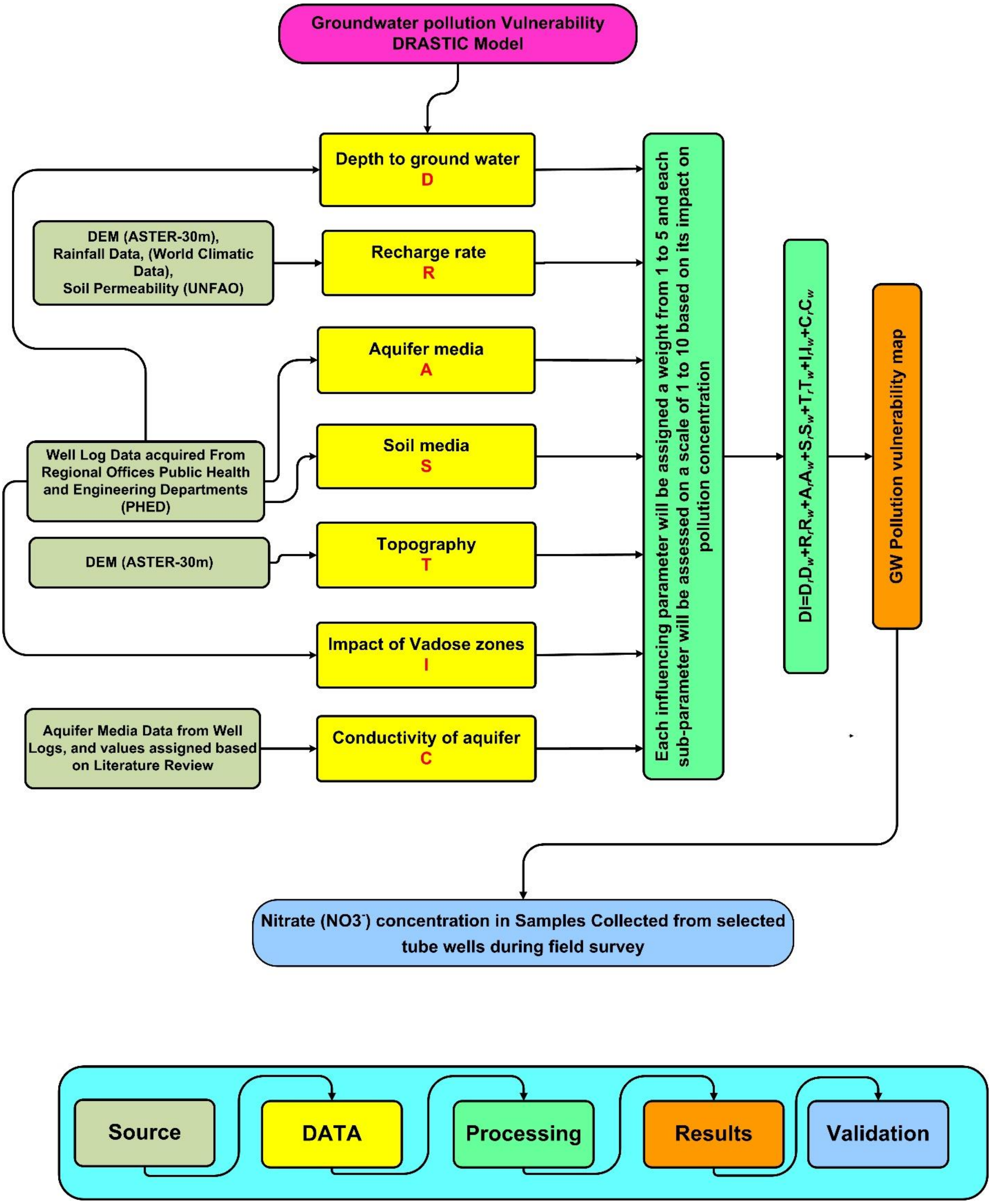


Figure 2: Illustrating DRASTIC Methodology

Model Validation

A variety of methods can be used to validate groundwater susceptibility mapping, such as the coefficient of correlation among groundwater vulnerability and actual contamination incidence, the association among severe levels of nitrate and vulnerability categories, the F statistic variance estimation (Lake et al., 2003), and level variance (Stigter et al., 2006). However, the typical strategy employed in this respect is to correlate vulnerability results with actual pollution incidence (Jhariya et al., 2019). As a result, the present study validated the DRASTIC technique using nitrate concentration, which is a common pollutant.

Table 2: Depicting groundwater vulnerability influencing parameters qualitative rank, rating and weight on DRASTIC based

S.No	Parameters/Sub-Classes	Rating	Qualitative rank	Weight	Area (km^2)	Area (%)
	Water Table Depth					
1	>321	1	Very Low	5	56.48	1.30
	241-320	2	Low		317.16	7.27
	161-240	5	Moderate		803.38	18.42
	81-160	7	High		1359.36	31.18
	< 80	9	Very High		1823.95	41.83
	Recharge Potential Factor					
2	1	1	Very Low	4	1039.51	23.84
	2	2	Low		1567.89	35.96
	3	5	Moderate		1169.11	26.81
	5	7	High		497.10	11.4
	7	10	Very High		86.68	1.99
	Aquifer Media Material					
3	Clay	1	Very Low	3	35.35	0.81
	Sand, Clay	2	Very Low		218.14	5.00
	Fine sand	3	Low		842.07	19.31
	Sand	6	Moderate		2488.05	57.06
	Gravel/Boulders	10	High		776.68	17.81
	Soil Media					
4	Clay	1	Very Low	2	370.32	8.49
	Sand, Clay	2	Very Low		1820.92	41.76
	Fine sand	4	Low		592.39	13.59
	Sand	6	Moderate		1502.52	34.46
	Gravel/Boulders	10	High		74.18	1.70
	Topography (Slope in percent)					
5	>20.1	1	Very Low	1	51.90	1.19
	14.1-20	3	Low		194.02	4.45
	8.1-14	5	Moderate		1067.30	24.48
	4.1-8	8	High		1825.31	41.86
	<4	10	Very High		1221.80	28.02
	Vadose Zone Material					
6	Clay	1	Very Low	5	106.68	2.45
	Sand, Clay	2	Very Low		385.99	8.85
	Fine Sand	4	Low		497.64	11.41
	Sand	6	Moderate		1971.53	45.22
	Gravel/Boulder	10	High		1398.49	32.07
	Hydraulic Conductivity cm/s					
7	$<10^{-7}$	1	Very Low		35.35	0.81
	10^{-5} - 10^{-7}	2	Very Low		218.15	5.00
	10^{-3} -10^{-5}	4	Low		842.08	19.31
	10^{-1} - 10^{-3}	6	Moderate		2488.07	57.06
	$>10^{-1}$	10	High		776.68	17.81

Results

Utilized parameters

Water table depth (D)

The DRASTIC model's one important factor, which is frequently employed to evaluate groundwater sensitivity to contamination, is the water table (WT) depth (Muhammad et al., 2015). It describes the dimension of the zone of unsaturation as the elevated gap from ground surface to groundwater level (WT) (Akiang et al., 2025). Such factor is very important because it affects how long contaminants will take to move across the soil and zone of unsaturation and how much attenuation they can withstand prior to arriving at an aquifer body (Jafarzadeh et al., 2024). However, the aquifer pollution risk is inversely correlated with WT depth (Ghosh et al., 2021). The highest DRASTIC influence weight 5 assigned to parameters water table depth (D) along with vadose zone material (I). The phreatic level is highly variables and classified into 5 zones ranges from <80 to >321feet employing equal interval method. Each phreatic zone was rank according to DRASTIC rates (1-10). Water table zone <80 feet cover 42% area with rate value 9 means very highly susceptible to contamination, concentrating the north, central, and the basin northwestern parts as result of the major rivers flowing and the canal system. The deepest zone >321 feet indicate very low vulnerability with rating 1 (accounting 1% area) (Fig3A. Illustrates spatial distribution).

Net Recharge Capacity

The volume of rainwater or other sources of water that seeps across the underlying strata and eventually approaches the aquifer is referred to as net recharge (Chakraborty et al., 2022). It has a substantial effect on groundwater susceptibility because net recharge controls the transmission of contaminants from the earth surface towards the aquifer (Udosen et al., 2024). It takes a variety of physical and chemical pollutants from both soil media and the vadose zone to the aquifer system (Gonçalves et al., 2023). However, safeguarding freshwater reservoirs and maintaining long-term sustainability need knowledge of the correlation between groundwater recharge and susceptibility (Polemio & Voudouris, 2022). The study area net recharge was computed using Eq. 1, because the research region did not have any accessible data for net recharge. The Bannu basin net recharge was categorized into five factor values: 1, 2, 3, 5, and 7. The very low, low, and moderate net recharge potential areas with drastic ratings 1, 2, and 5 reflect very low, low, and moderate vulnerability to contamination. High and very high net recharge (factor value 5 and 7) with drastic rating 7 and 10 shown high and very high pollution potential (Table 2; Fig3B).

Aquifer Media

Aquifer media is the term used to describe both consolidated and unconsolidated geo-materials that hold water contents (Bera et al., 2021). Groundwater susceptibility is considerably control by the water-holding medium structure since numerous materials possess different porosities and permeability level (Amiri et al., 2020). It controls how long the contamination takes and how it gets to the groundwater reservoir. As the water seeps within, numerous processes occur, including purification, ion exchange, as well as sorption (Guo et al., 2023). In the five resultants aquifer media zones, the clay nearly impermeable nature gets a DRASTIC rating value of 1, means no or little effect on groundwater pollution. Sand, clay and fine sand zones with ratings 2 and 3 has less conducive to pollution susceptibility. Sand having moderate permeability get drastic rating value 6 and are moderately vulnerable to pollution, covering the largest portion of the basin. The fifth class (Gravel/Boulders material) with high permeability was given a rate value 10 indicating high susceptibility to contamination (Fig. 3C). Consequently, the aquifer media map results demonstrated that the basin has moderate to high groundwater vulnerability.

Soil media

Soil media, the most superficial and mature stratum of the earth's crust, is where significant biotic activities happen and can function as a major buffer to prevent pollutants from intruding and reaching aquifer material (Baki & Ghavami, 2023). The medium continuously regulates the locale's groundwater replenishment and prevents impurities from draining across the strata (Valhondo et al., 2020). Soil media enables effectively eliminating pollutants through absorption and abatement properties. However, soil has a considerable impact upon pollutants concentration and consequent downward mobility to vadose zone (Xu et al., 2023; Zhang et al., 2023). In the Bannu basin, the soil media is divided into five groups; notably, clay, sand with clay, fine sand, sand, and gravel with boulders were assigned DRASTIC index rates of 1, 2, 4, 6, and 10, correspondingly (Fig. 3D).

Topography (Slope) in Percent

The term topography refers to the ground surface slope variability (Abunada et al., 2021). It has a direct relationship to surface flow (Segura-Méndez et al., 2024). This component drastically impacts both the infiltration rate and runoff potential rate. The likelihood that contaminants may permeate, concentrate, and pollute groundwater is evidently indicated by the terrain (Rehman et al., 2024). The spatial distribution of slope classes is shown in figure (Fig. 3E). The highest rating 10 was given to class <4 (flat slope), indicating very highly conducive to vulnerability. Class 4.1-8 with rate 8 is highly vulnerable to contaminants, while slope classes 8.1-14 and 14.1-20 have moderate and low contamination vulnerability. The least rate (1) is assigned to steep slope (>20.1%), having a very low effect on groundwater pollution (Table 2).

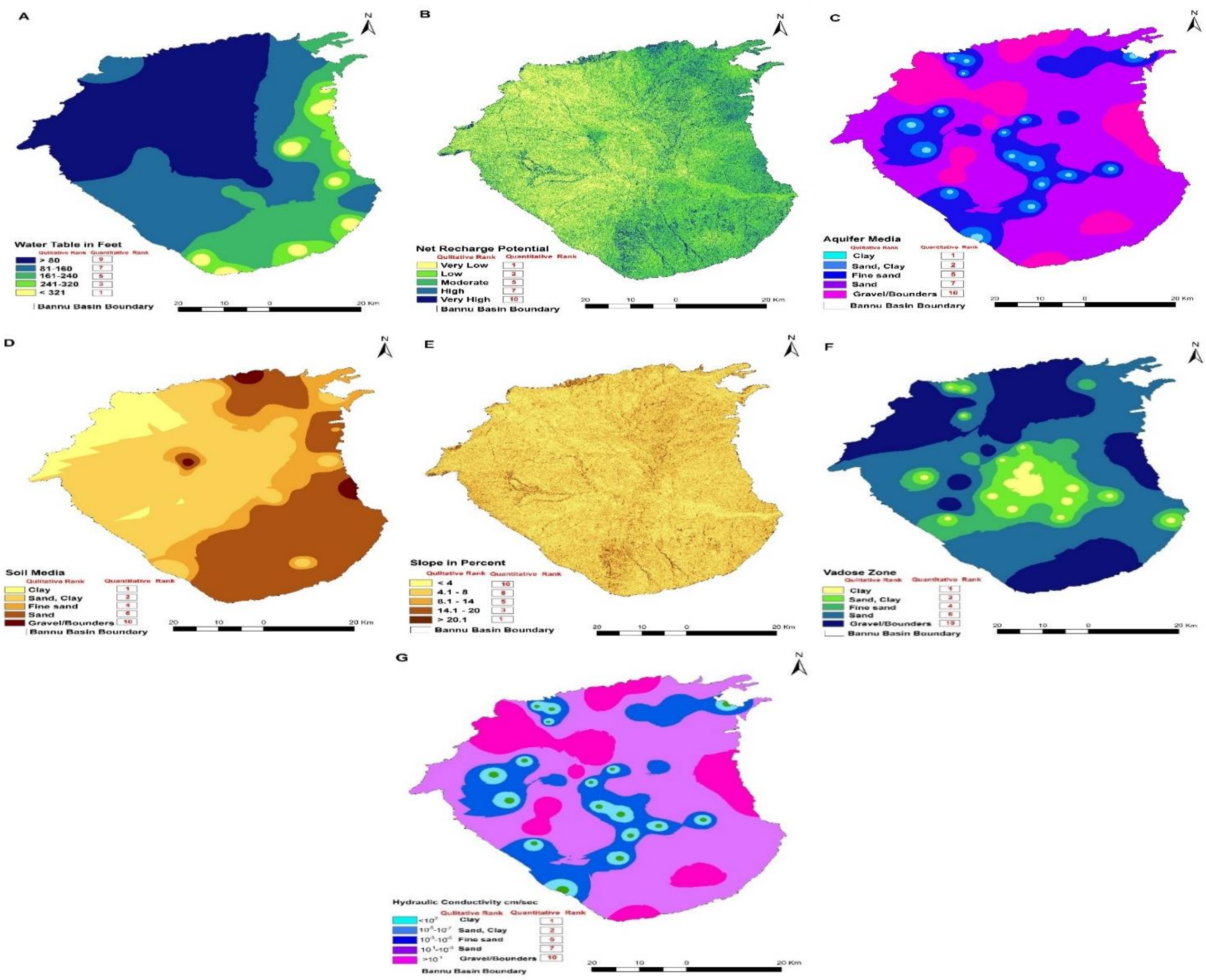
Vadose Zones

The vadose zone is the desiccated stratum that exists between the top ground surface and the WT, which significantly influences contaminants movement (Shakoor et al., 2020). The zone serves as a conduit for interactions across the region of saturation (water table) as well as the land surface (Akhtar et al., 2022). It is primarily reliant upon the soil medium permeability potential and the attenuation properties (Jmal et al., 2022). By operating as a pathway, the area of vadose play a crucial role in regulating the amount of pollutants filled water entering the aquifer (Van Wyk et al., 2024). The study results indicate that the three vadose zone categories, such as clay, sand clay, and fine sand, are mainly concentrated in the central basin area with rates values of 1, 2 and 4, respectively. Rating values 6 and 10 were assigned with moderate and high permeability capacity to sand and gravel/boulder. The investigation outcome shows that approximately 80% of the area under investigation fall in a moderate to highly vulnerable zone. However, based on vadose zone analysis, the Bannu basin has a greater possibility of groundwater contamination (Fig.3F).

Hydraulic conductivity

The aquifer body potential to move water is known as hydraulic conductivity (Ahirwar & Shukla, 2018). This aquifer property governs how fast groundwater can move under a specific hydraulic gradient (Umar et al., 2022). This is a crucial feature that affects the velocity at which groundwater passes within the threshold of the saturated zone. Particle size, permeability, and the state of media saturation are some of the variables that affect it (Ahmed et al., 2022). The peril of vulnerability increases with higher hydraulic conductivity (Ahirwar & Shukla, 2018). The aquifer body material was categorized into 5 groups. The hydraulic conductivity value is assigned to each and every group using existing literature owing to no data availability. The clay has the least HC $<10^{-7}$ cm/s cover small patches in the central basin and eastern mountainside. Sand clay and fine sand material HC is $10^{-5} – 10^{-7}$, and 10^{-3} -10^{-5} cm/sec also cover a small portion of the central and eastern mountainside (Bhittani range), respectively. HC 10^{-1} - 10^{-3} cm/s with rate value 7 has the potential of moderate pollution susceptibility and shares the largest portion of the basin aquifer body area, while gravel/boulder has the highest HC $>10^{-1}$ cm/s with rating 10 having greater chances of groundwater contamination (Fig.3G).

Figure 3: Illustrating Bannu Basin (A) Water table depth, (B) Net recharge, (C) Aquifer media, (D) Soil media, (E) Topography, (F) Vadose zone, (G) Hydraulic conductivity



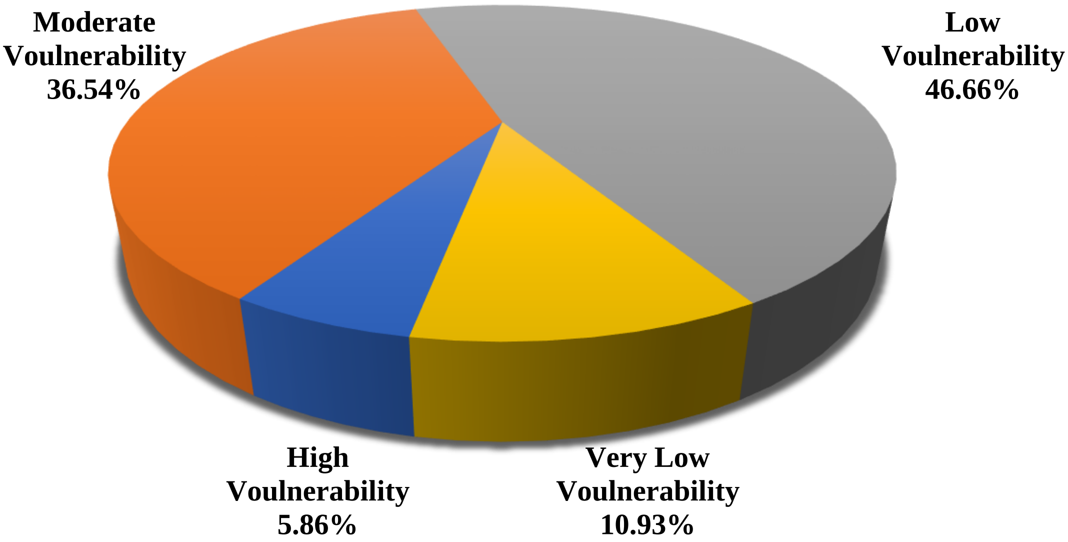
Bannu Basin groundwater vulnerability

The Bannu Basin groundwater vulnerability resultant map were divided into four distinct classes; varying from very low to high vulnerable zones (Fig. 5). The very low vulnerable zones prevail on 476.72 Km^2 (accounting 10.93% of the basin area). Such vulnerable zone concentrated in the basin central due to clay material low permeability nature present in vadose zone, and aquifer media. The largest area 2034.56 Km^2 (46.66% nearly half of the basin) share by low vulnerability zone followed by moderate vulnerable zone accounting 1593.41 Km^2 (36.54% area of the total). High vulnerability occupy small portion of 255.63 Km^2 which account 5.86% of the basin (Table 3). High vulnerability exists in the basin northern parts, especially found in urban area (Bannu city) and some pixel lies in northwestern, southern and along eastern boundary side. Consequently, based on analysis outcomes the Bannu Basin possess low to moderate pollution vulnerability owing to soil media less permeable nature, predominance of vadose zone clay and sand with clay material and moderate hydraulic conductivity and phreatic zone.

Table 3: Showing Bannu Basin Aquifer Vulnerable Zones to Contamination Classes, their Area and Percentages

S. No	Aquifer Vulnerability	Area in Km^2	Area %age
1	High Vulnerability	255.63	5.86
2	Moderate Vulnerability	1593.41	36.54
3	Low Vulnerability	2034.56	46.66
4	Very Low Vulnerability	476.72	10.93
Total		4360.33	100.00

Figure 4: Depicting Groundwater Vulnerable Zones of Bannu Basin with Area Percentage

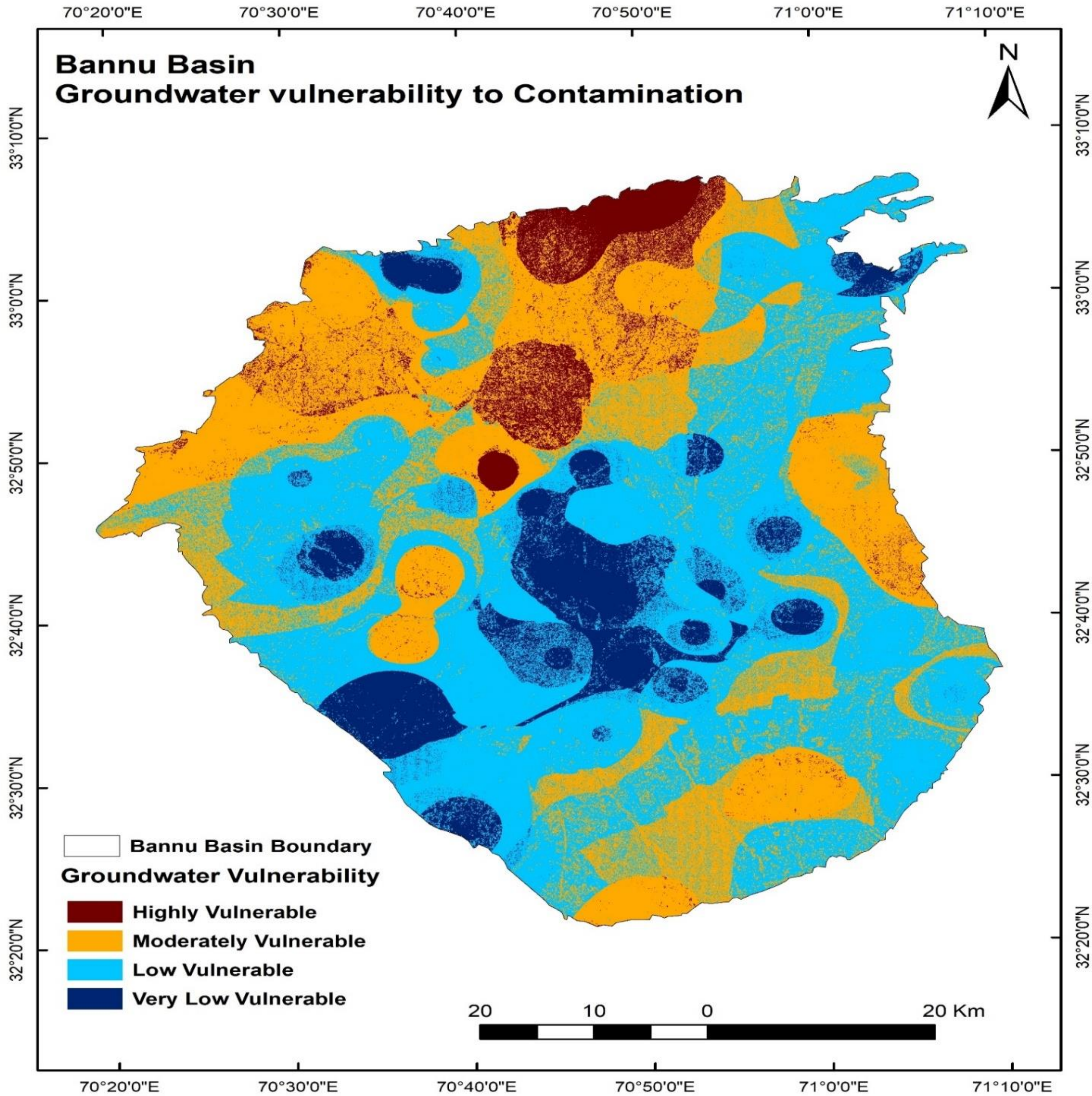


Validation

The validation of the DRASTIC model for the groundwater vulnerability assessments is essential to ensure its reliability and validity. The groundwater nitrate concentration is used to validate DRASTIC vulnerability output map of the Bannu Basin. Water samples of 66 wells were gathered in 250 ml plastic bottles and then analyzed employing the American Public Health Association (APHA) procedure (20^{th} edition) at the PHE water quality laboratory in Peshawar. Nitrate concentration were found to vary from 1.1 to 340mg/L. The vulnerability map was superimposed with the nitrate samples point. Figure 6 depicting spatial distribution of DRASTIC validation using nitrate. The spatial variations within the basin is indicated by proportional circles of various size, which reflect the amount of nitrate measurements.

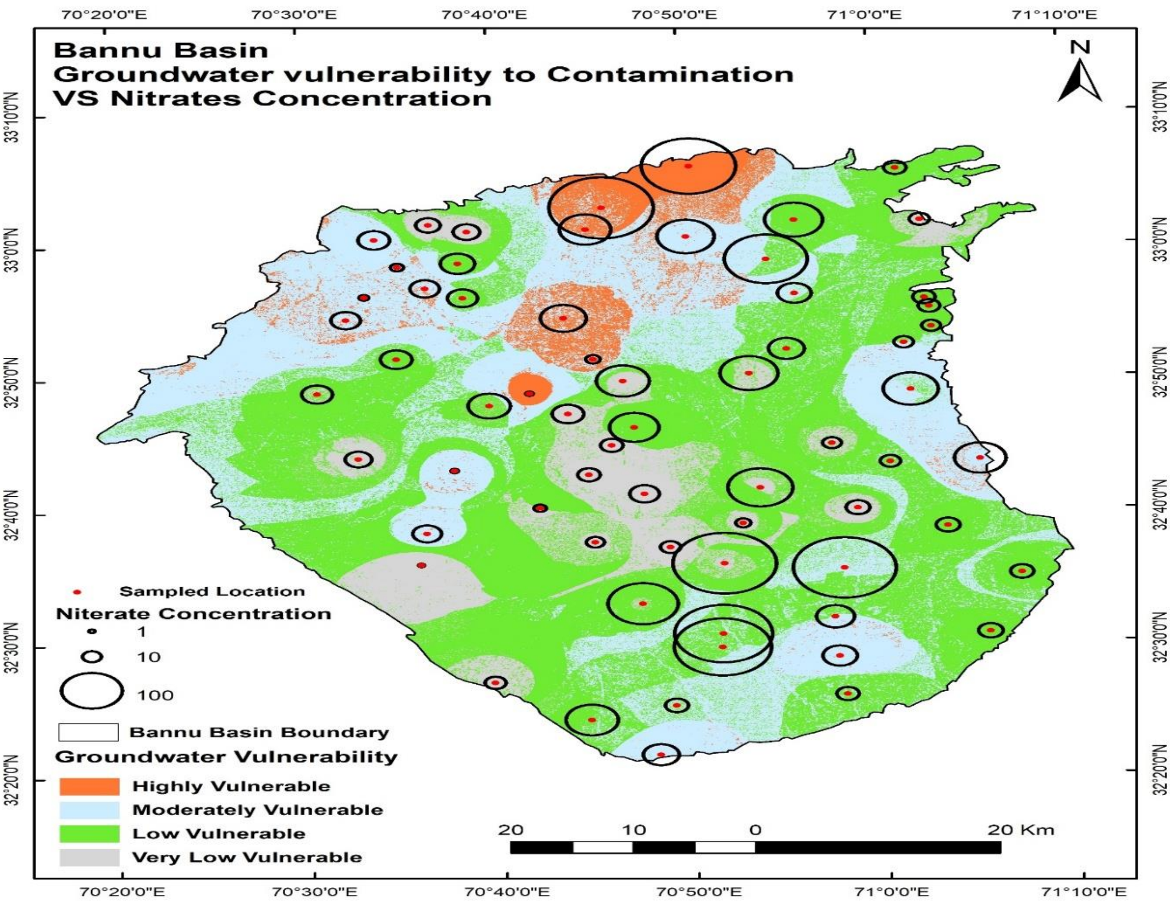
According to the DRASTIC results, zones classified as highly vulnerable and moderately vulnerable are mostly tied with location containing greater nitrate contents. Such spatial relationship demonstrates that the real quantities of nitrate pollution and the modelled vulnerability map show a strong positive correlation. The model consistency is further supported by the fact that zones classified as low and very low vulnerability usually lesser nitrate contents. Domel city (84 mg/L), Latambar (277.8 mg/L), Musa khel (340 mg/L), and Naurang city (89 mg/L) exhibit the highest levels of nitrate circles located in the northern and the northwestern parts, which are identified as high potential vulnerability. This suggests a

Figure 5: Illustrating Groundwater Vulnerability Various Zones Spatial Distribution



substantial human impact, such as urbanization, runoff from agriculture, waste water intrusion, and shallow water table. In basin southern parts, a few unusual sampling sites with raised nitrate concentration in different less vulnerable zones are probably due to specific point sources (such as wastewater discharge, agriculture fertilizers hot-spots) or subsurface medium variability that are not determined by up by the regional DRASTIC parametrization processes. The consensus corresponds to alignment with hydro-geological factors that are considered to improve nitrate distribution, such as narrow vadose zones, soil with coarse grains or alluvium, low water level, and enhanced recharge and strong hydraulic conductivity linked with higher-vulnerable areas. However, due to the preponderance of clay-based natural material deposited by the rivers Kurram and Tochi and their tributaries, the center and the basin southern areas, which are largely attributed by low vulnerability, exhibit little nitrate content.

Figure 6: Showing Bannu Basin Groundwater Vulnerability to Contamination vs Nitrate Concentration



Discussion

Despite being an essential resource for agriculture and rural water supply, groundwater in the Bannu Basin is under threat from localised pollution, according to current monitoring and water-quality assessments (Shakoor et al., 2025). To visualise the intrinsic aquifer vulnerabilities and define spatially explicit zones encompassing very-low to high susceptibility, the current study employed a GIS-based DRASTIC framework. That made it possible to compare previous regional uses of the approach (Barbulescu, 2020). Data on the seven parameters necessary to compute the DRASTIC model are often collected as location-based (point) data from well logs/strata charts. Several investigations in this field have applied two standard interpolation techniques: notably, kriging and IDW (Baki & Ghavami, 2023). IDW and other GIS-based procedures are used in the current research to map the model's required parameters. Each factor's significance in assessing the risk of groundwater pollution is prioritised based on the available literature and expert judgement.

Both Water table depth and vadose zone material were given the most significant DRASTIC influence weight of 5, followed by net recharge potential, which received a four weight value; aquifer media and hydraulic conductivity were assigned three weight values; and soil media was given two weight values. The lowest-weighted one was transferred to the topography (slope, %) of the Bannu Basin.

Water table depth is significant because it affects how long contaminants take to travel through the soil, the zone of unsaturation, and the amount of attenuation they can withstand before reaching an aquifer body (Jafarzadeh et al., 2024). An elevated WT generally reduces the potential for groundwater pollution by providing an additional route and additional space for natural attenuation mechanisms, including adsorption, infiltration, purification, and biodegradation (Akiang et al., 2025). The shallow WT indicates a greater risk of pollution, reflected in the DRASTIC analysis, which gives them a higher score of 9, concentrating on the north, central, and northwestern parts due to the major rivers flowing and the canal system.
Recharge has a substantial effect on groundwater susceptibility and a direct relationship to GW contamination risk (Udosen et al., 2024). Even though recharge evaluations must be considered in groundwater management plans by environmental managers and policymakers to avoid pollution and ensure water sustainability. The highest DRASTIC score (10) is assigned to a very high recharge area due to its high pollution potential. In contrast, clay with very low net recharge received a rate of 1, indicating minimum pollution vulnerability.
Aquifer medium is a crucial tool for evaluating groundwater health (Guo et al., 2023). Consequently, the porosity and width of the underlying strata determine how contaminants move through them. Thicker, less permeable deposits are classified as having a lower potential for vulnerability because pollutants are more diluted and less likely to dissolve (George et al., 2025). Aquifer media was computed from 66 well logpoints by using the IDW interpolation technique. After computing the DRASTIC rate, each aquifer media subclass was assigned a pollution influence rating. The clay subclass's nearly impermeable nature receives a DRASTIC rating of 1, indicating little to no effect on groundwater pollution. The highest rate, 10, was given to the highly permeable subclass of gravels/boulders owing to a greater chance of contamination.
The most superficial and mature stratum of the earth's crust is the Soil media (Baki & Ghavami, 2023). Such an outer layer may serve as a significant buffer, preventing pollutants from entering the aquifer. Applying the IDW interpolation procedure to 66 well logs/strata charts point-based data, the resultant map was classified into five soil media zones. The lowest rate is assigned to the clay zone with low contaminant risk. The maximum risk pot, ra,tva0, was assigned to the gravel/boulder material, which was designated a 10 zone.
The term topography refers to the variability in ground surface slope (Abunada et al., 2021). Long-term water retention occurs in places with low slope angles or gentle slopes, which increases the likelihood of pollutant absorption via downward percolation of water, and vice versa. Using the ASTER Global Digital Elevation Model (ASTER GDEM), the slope was computed as a percentage for the study region. Based on the literature class (<4, flat slope), the maximal rate was 10, indicating very high vulnerability. The steep slope (>20.1%) received a rating of 1 for pollution vulnerability.
Another significant factor is the vadose zone, the desiccated stratum between the earth's surface and the water table (Shakoor et al., 2020). The same IDW interpolation procedure was used to calculate the vadose zone. The drastic rating assigned to clay material was due to its impermeable nature, which means areas with clay have low vulnerability to contamination. Rating values 6 and 10 were assigned to moderate and high permeability capacity for sand and gravel/boulder vadose zone material classes, which were to have high pollution vulnerability. The investigation outcomes show that approximately 80% of the basin area lies in a moderate-to-highly vulnerable zone.
Hydraulic conductivity is a crucial property that affects the velocity of groundwater flow through the saturated zone (Ahirwar & Shukla, 2018). In the DRASTIC model, hydraulic conductivity is one of the seven influencing parameters used to assess groundwater vulnerability, with higher values indicating a higher vulnerability potential (Zhang et al., 2023). The clay has the least HC (<10-7 cm/s), covering small patches in the central basin and the

eastern mountainside, while gravel/boulder has the highest HC (>10-1 cm/s), with rating 10 having a greater chance of groundwater contamination.

To enhance confidence in the vulnerability map, the model outputs were validated against field-collected nitrate concentrations to assess their reliability and robustness. This method has been shown to improve the efficiency of DRASTIC estimation when aligned with water-quality statistics. The basin revealed spatial trends in vulnerability that align with results from neighbouring Pakistani regions, where GIS- and remote-sensing-based vulnerability modelling has been helpful in resource evaluation. These patterns reflect the interactions among water depth, recharge rates, structural constraints, and land-use trends (Umar et al., 2022; Maqsoom et al., 2020; Shakoor et al., 2020). Hence, our findings not only identify areas that require greater attention in terms of monitoring and mitigation strategies but also illustrate how integrated and validation processes may guide groundwater governance in semi-arid basins.

Conclusion

The aquifer vulnerability of the Bannu Basin, utilising the DRASTIC technique, revealed apparent spatial variability in vulnerability to pollution. According to the results, about 5.86% (255.53 km2) of the region is classified as highly vulnerable, 36.54% (1543.41 km2) as moderate, 46.66% (2034.56 km2) as low, and 10.93% (476.72 km2) as extremely low susceptibility. Highly sensitive areas are generally found in regions with significant recharge capacity, a relatively low water table, and a porous soil texture that allows contaminants to flow more easily. In contrast, clay-rich soil, a low recharge rate, and more protective cover are associated with the low- and very-low-vulnerability zones, thereby lowering the risk of contamination. The model's validation using nitrate concentration statistics showed a strong positive correlation. It demonstrated that places with high and moderate susceptibility are associated with high nitrate concentrations, thereby substantiating the model's consistency and reliability. The results indicate that the primary causes of groundwater pollution across the study area are human activities, including agricultural practices and improper waste disposal. In data-scarce regions, the DRASTIC model was found to be a valid, reliable, and efficient method for evaluating groundwater intrinsic vulnerability. It offers core insights for managing groundwater conservation and sustainable administration. To protect groundwater, it is essential to prioritise highly vulnerable areas, conduct regular water-quality checks, limit on-farm chemical use, and carefully manage land use. To further improve aquifer preservation and reduce pollution concerns, awareness campaigns and legislative initiatives must be supported. Future research could enhance the model's assessment capabilities and contribute to the sustainable management of the basin's groundwater resources by incorporating additional characteristics, such as land-use dynamics.

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