Impacts of Climate Variability and Urban Expansion on Groundwater Systems in Mansehra

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Groundwater serves as the principal source of domestic water supply in Mansehra District, Khyber Pakhtunkhwa, Pakistan. However, rapid urbanization and climate change have increasingly impacted groundwater quality and recharge dynamics in the region. This study investigates groundwater quality and identifies potential recharge sources under shifting environmental conditions. A total of eleven water samples were collected from wells, rivers, and surface channels across five distance-based zones (0–200 m, 201–400 m, 401–600 m, 601–800 m, and 801–1000 m) relative to the nearest river. The samples were taken in sterile, dry containers and were transported within 24 hours to the Pakistan Council of Research in Water Resources (PCRWR), Islamabad, for detailed physicochemical analysis. Parameters measured included pH, electrical conductivity (EC), total hardness, alkalinity, turbidity, calcium (Ca), and potassium (K). The findings show extensive groundwater quality deterioration in areas subject to high urban activity and climatic fluctuation. More specifically, samples from Baffa showed higher hardness, Ca, and K levels above WHO allowable limits, indicating contamination potential. On the other hand, samples from Nokot and Ichria mostly met WHO standards, with turbidity being the only parameter of concern. Comparison of analyses of well, river, and pond samples revealed rivers and surface water bodies as the preeminent sources of groundwater recharge. The findings highlight the imperative need for sustainable groundwater management practices to mitigate the adverse impacts of anthropogenic stresses and climate change in the Mansehra Basin.

Keywords: Climate Change, Groundwater Quality, Recharge

Introduction:

Groundwater is a vital natural resource catering to domestic, irrigation, and industrial water needs globally, particularly in water-scarce regions and developing countries [1]. In Pakistan, where freshwater shortage is evolving as an acute issue due to both human-induced forces and climate change, groundwater has become the central component of the national water supply system. This is especially true in areas that are urbanizing, for instance, Mansehra, where dependency on aquifers is increasing amid development pressure and a growing population [2]. There have been extreme changes in rainfall patterns over the past decades, rising temperatures, and unpredictable seasonal patterns combined with unregulated urban sprawl, all of which have increasingly undermined the quality and quantity of groundwater resources [3].

In the Mansehra District of Khyber Pakhtunkhwa, population growth and urbanization have put aquifer systems under extreme pressure, producing issues such as over-drafting, loss of natural recharge, and domestic and industrial effluent pollution [4]. Climate variability—against the background of non-uniform rainfall and frequent droughts—has also increased the vulnerability of groundwater resources in the region [5]. There is a need to identify the synergistic impacts of climate variability and urbanization on groundwater systems to develop adaptive and sustainable water management strategies.

Although groundwater quality research has been conducted in different regions of Pakistan, no prior study in the Mansehra District has established the prominent sources of groundwater recharge under the joint effect of climate variability and urbanization through a systematic framework. Previous studies have typically evaluated water quality without incorporating recharge source identification, spatial proximity analysis to riverine systems, and comparative analysis of several hydrological sources like wells, rivers, and ponds. This research fills this gap by combining distance-based spatial sampling with exhaustive physicochemical characterization, thus delivering novel scientific findings that couple hydrochemical properties with recharge source apportionment in a climatically sensitive and rapidly urbanizing basin. This study investigates the interconnected impacts of climate variability and urbanization on Mansehra's groundwater systems. Through systematic sampling and physicochemical analysis of water samples from various hydrological sources and areas with varying proximities to river systems, this study aims to ascertain patterns of contamination and the dominant recharge source. The specific objectives of this study were: (a) to assess the quality of surface and groundwater in the Mansehra region, (b) to determine the possible source of groundwater recharge.

Materials and Methods:

Study Area and Spatial Zoning:

The research was carried out in Mansehra District, Khyber Pakhtunkhwa, Pakistan, which is rapidly urbanizing and is also subject to increased climate variability. To investigate the spatial impact of surface water bodies and urbanization on the recharge and quality of groundwater, the district was demarcated into five zones based on proximity to the nearest river. These zones were: Zone 1 (0–200 meters), Zone 2 (201–400 meters), Zone 3 (401–600 meters), Zone 4 (601–800 meters), and Zone 5 (801–1000 meters). Zoning assisted in the trend analysis of groundwater quality concerning natural recharge areas and land-use gradients.

Field Survey and Metadata Collection:

The study consisted of a field survey to obtain samples of groundwater and surface water and background information regarding the hydrological infrastructure. Data such as well depth, construction date, and precise distance from the river were collected for each groundwater sampling site during the survey. These metadata points were required to interpret the age, depth, and spatial position of wells concerning potential recharge zones and urban use, thus allowing a more detailed interpretation of the water quality variability.

Water Sample Collection and Preservation:

Eleven water samples were drawn from different hydrological sources in Mansehra, which included eight from groundwater wells and three from surface water bodies, such as rivers and channels. All the samples were drawn in sterilized, clean polyethylene bottles to avoid external contamination, and 0.01% nitric acid was added to the samples. The bottles were immediately sealed and transferred to the Pakistan Council of Research in Water Resources (PCRWR) within 24 hours of sample collection to facilitate early analysis. Figure 1 presents the flow diagram of the methodology.

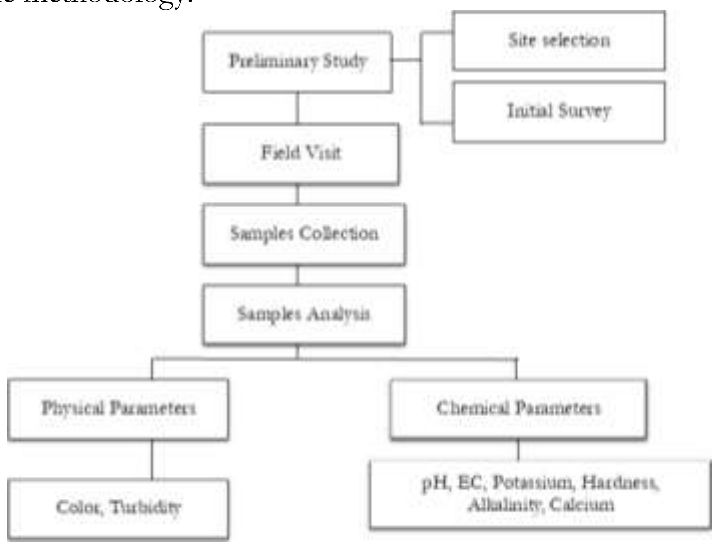

Figure 1. Flow Diagram of the Methodology

Laboratory Analysis of Physicochemical Parameters:

The collected samples were subjected to thorough laboratory analysis to evaluate primary physicochemical parameters. The pH, electrical conductivity (EC), turbidity, total hardness, and alkalinity are basic water quality indicators. Critical cations and anions—calcium (Ca^{2+}), and potassium (K^{+})—were also determined to assess geochemical processes and sources of contamination. The outcomes were compared to the national water quality standards by the Pakistan Environmental Protection Agency (Pak-EPA) and international standards adopted by the World Health Organization (WHO).

Correlation Analysis:

Pearson's correlation coefficient (r) was used to determine the relationships among physicochemical water sample parameters, such as pH, EC, well depth, and distance from the river. The analysis sought to detect possible trends and dependencies between the observed variables. Correlation analysis was conducted using Microsoft Excel.

Results and Discussion:

Table 1 presents important physicochemical parameters like source type, depth, year of construction, river distance, pH, electrical conductivity (EC), and color of the water samples collected from various locations in Mansehra. All samples were colorless, i.e., no visible contamination existed. The pH levels ranged from 6.83 to 8.43, which is within the acceptable range for drinking water according to WHO standards (6.5–8.5) [6], showing slightly acidic to moderately alkaline water quality. In a study conducted in the District of Swat, it was shown that the samples collected from the region were within the range of 7.0 to 8.21 [7].

Electrical conductivity (EC) ranged from 275 µS/cm to 1566 µS/cm, with the highest found in Baffa's well samples, namely Sample R2S3 (1566 µS/cm). Higher EC indicates increased dissolved ion levels that can occur due to geological impacts, agricultural runoff, or infiltration of wastewater (Singh et al., 2020). Interestingly, wells that were located farther from the river had greater depths, indicating a relationship between well location and accessibility to the aquifer. The pattern indicates that as distance from the river increased, groundwater was being drawn from deeper aquifer layers, likely to maintain the supply of water because of low surface water recharge [8].

Figure 2 indicates turbidity and total hardness values of the water samples. Total hardness was 122–572 mg/L, exceeding WHO's maximum allowable value of 500 mg/L in Baffa's water samples, especially Sample R2S3, with the highest hardness value (572 mg/L). This suggests an excessive availability of calcium and magnesium ions**, most commonly** associated with natural geological origins or contamination from domestic effluent [3]. Increased hardness affects water palatability and results in scaling of pipes and appliances. Turbidity, while not given in numeric terms, varies in levels by location and can indicate suspended solids or microbial growth [9].

Table 1. Physicochemical Parameters of Water Samples from Different Zones in Mansehra

Location	Samples ID	Source	Depth	Year of Construction	Distance from the River	Color	EC (µS/cm)	pH
Nokot	R1S1	River	__	__	__	Colorless	431	7.93
	R1S2	Well	25 ft	2017	150m	Colorless	530	7.25
	R1S3	Pound	__	__	400m	Colorless	474	7.69
	R1S4	Channel	__	__	720m	Colorless	393	8.43
Baffa	R2S1	River	__	__	__	Colorless	373	8.39
	R2S2	Well	22 ft	2021	162 m	Colorless	1320	7.38
	R2S3	Well	60 ft	2022	301 m	Colorless	1566	7.35
	R2S4	Well	45 ft	2018	602 m	Colorless	1022	6.85
Icheeria	R3S1	River	___	___	__	Colorless	275	7.77
	R3S2	Well	38 ft	2014	210 m	Colorless	491	7.3
	R3S3	Well	67 ft	2013	502 m	Colorless	324	6.83

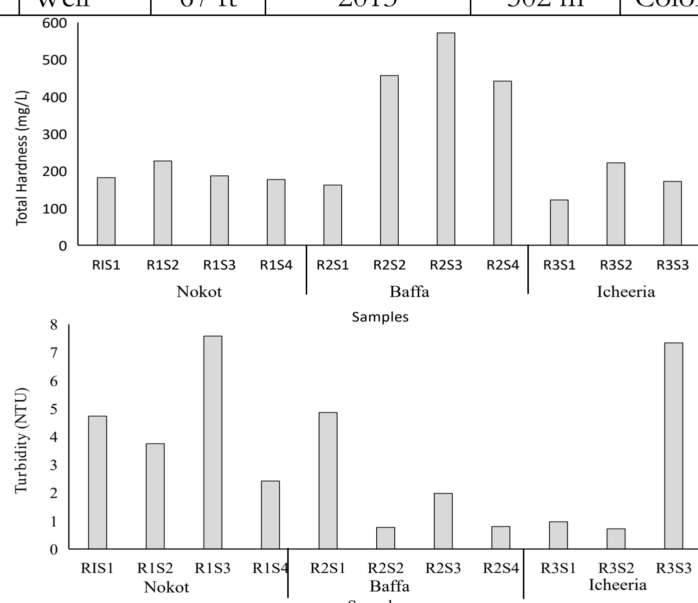

Figure 2. Total hardness and turbidity of water samples collected from the study area.

As indicated in Figure 3, water sample alkalinity varied between 112–367 mg/L. The lowest alkalinity was reported in Ichria and Baffa river samples, whereas the highest alkalinity was reported in Baffa well samples. High alkalinity in water is commonly caused by high concentrations of bicarbonates and carbonates, which act as pH buffers and are indicative of the geological nature of the aquifer [10]. The high alkalinity in the wells at Baffa can also be attributed to agricultural inputs or urban runoff altering the chemistry of the groundwater.

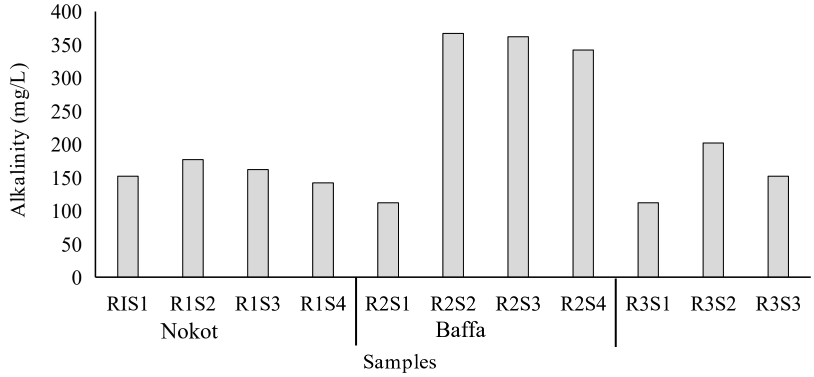

Figure 3. Alkalinity of water samples collected from the study area.

The levels of calcium and potassium, as presented in Figure 4, differed considerably among the sampling points. The levels of calcium varied from 14 mg/L (Ichria) to 141 mg/L (Baffa), and those of potassium varied between 2.5 mg/L and 90 mg/L, with the maximum values also obtained in the wells of Baffa. Increased calcium and potassium could be due to mineral dissolution, fertilizer application, or seepage of wastewater, all of which are exacerbated in urbanizing areas. High levels of potassium, especially in Baffa, could suggest the impact of human activities like intensive farming or failing septic systems [11][12]. Note that the study relies on 11 samples taken from representative hydrological sources within five spatial zones. Although this small sample size limits statistical generalization and spatial interpolation of results, the sampling scheme was designed to reflect the diversity of source types and river proximities in the study region. Therefore, the results should be considered as baseline data that can inform future, larger-scale monitoring of seasonally resolved precipitation and atmospheric composition in future research.

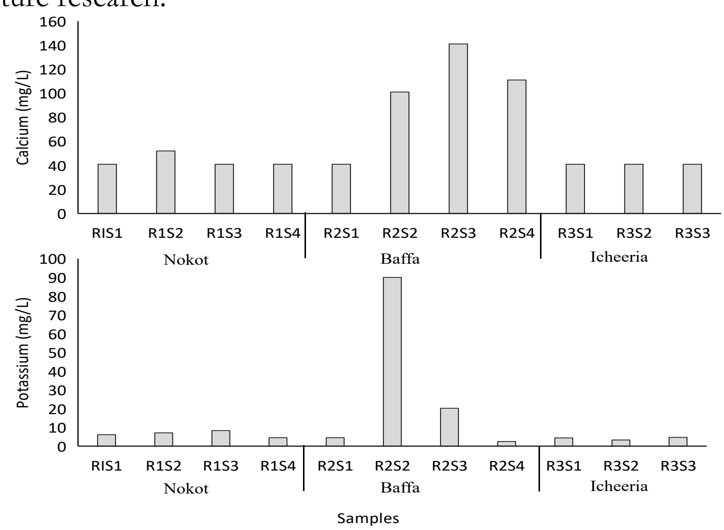

Figure 4. Calcium and potassium levels of water samples collected from the study area.

The correlation matrix (Table 2) shows coherent hydrogeochemical trends throughout the Mansehra dataset. Electrical conductivity (EC) co-varies nearly perfectly with total hardness ($r = 0.987$) and alkalinity ($r = 0.958$), and moderately with potassium ($r = 0.589$), indicating that bulk salinity, carbonate buffering, hardness, and K^+ enrichment increase and decrease together—consistent with carbonate-dominated water–rock interaction supplemented by surface inputs. By contrast, turbidity has weak–moderate negative correlations with EC ($r = -0.553$), alkalinity ($r = -0.639$), and hardness ($r = -0.583$), indicating that more mineralized water is also clearer, which may be due to percolation filtration and longer residence. The hydrogeologic context also plays a role: distance from the river is highly correlated with well depth ($r = 0.668$), suggesting that locations further from surface water depend on deeper aquifer horizons; EC has only a weak negative correlation with distance (r = −0.303) and effectively none with depth (r = −0.052), suggesting that mineralization is more influenced by geochemical processes than by well depth itself. Potassium declines with distance (r = −0.467) and depth (r = −0.497), suggesting that near-stream and shallower areas are more impacted by surface-sourced inputs (e.g., agricultural return flows or wastewater leakage). pH is modestly correlated with distance (r = 0.298) but moderately reduced in deeper wells (r = −0.534), consistent with enhanced buffering/CO_2 effects with depth; its correlations with EC (r = −0.206) and other ions are small. Lastly, alkalinity and hardness are strongly correlated (r = 0.971), supporting a single source of carbonates. Collectively, these trends point to a carbonate-dominated aquifer where proximity to rivers controls the depth of wells and the level of surface control, and areas of greater mineralization have lower turbidity. (Since n = 11, these correlations must be viewed as suggestive rather than conclusive and are best confirmed with larger, seasonally resolved collections.)

	Distance from River	Depth	pH	EC	Turbidity	Alkalinity	Total Hardness	Potassium
Distance from River	1							
Depth	0.667854149	1						
pH	0.297826221	-0.53403	1					
EC	-0.303265751	-0.05229	-0.20592	1				
Turbidity	0.168819954	0.531297	-0.02984	-0.553376	1			
Alkalinity	-0.264420195	-0.12602	-0.35125	0.9583938	-0.6386494	1		
Total Hardness	-0.230417222	0.019682	-0.28846	0.9873084	-0.5827143	0.97122616	1	
Potassium	-0.467287703	-0.49706	0.008419	0.5887254	-0.3325069	0.5896645	0.490222333	1

Conclusion:

The study showed that the growing population and urbanization significantly affected the groundwater level. The depth of the water level increased as the distance of the well from the river increased. The parameters were within the permissible levels of the NEQS, except for turbidity, total hardness, calcium, and potassium. Among the collected samples from various areas, it was shown that the water in Baffa was contaminated.

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The manuscript has not been published or submitted to any journal. Furthermore, all the authors contributed to the manuscript.

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