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Mapping Water Resources and Potential Recharge Zones: A Watershed-Based Study of Tarilum Watershed, Drujaygang, Dagana Dzongkhag

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Abstract

This study assessed the ecological integrity and functionality of the Tarilum watershed using a watershed-based approach. Due to the lack of alternative watersheds nearby, this watershed is critical for sustaining the gewog's water requirements, both for drinking and irrigation. The assessment, carried out using the 2016 watershed classification guidelines, GIS, and hydrogeological studies, categorized this watershed as 'Degraded category', primarily due to environmental stressors such as soil erosion, infrastructure development, and unsustainable land use practices. The study further identified such problems as porous and disturbed recharge zones and steep slopes in the watershed's upper regions that require immediate management interventions. The results indicate a necessity for strategic land-use planning and implementation of erosion control measures to safeguard groundwater recharge and maintain water availability. Recommended management strategies include afforestation, sustainable land management, and recharge zone protection interventions. Adopting these strategies is anticipated to significantly enhance the watershed's resilience, ensuring sustainable water availability and long-term ecological health.

Keywords: Dip, Dip direction, Ecological integrity, Recharge areas, Water demand, Water security, Watershed

Introduction

Water is a vital ecosystem-based resource that supports human well-being and sustains ecological balance (Partnerships and Cooperation for Water, 2023). Effective water management, particularly through integrated watershed approaches, is essential for maintaining water availability and ecosystem services in the face of increasing environmental and anthropogenic pressures.

Global and regional studies highlight the value of integrated watershed management as a framework to optimize ecosystem functions while safeguarding water security for future generations (Wang *et al*., 2016; Stosch et al., 2017; Vogl *et al*., 2017). Despite this, localized assessments remain limited, particularly in ecologically sensitive and rapidly developing areas like Drujaygang Gewog. Watersheds in such regions are increasingly threatened by land-use change, infrastructure expansion, and declining ecological health (Sharma & Sharma, 2005; Watershed Management Division [WMD], 2021).

Dagana Dzongkhag comprises 719 water sources distributed across 21 sub-watersheds, many of which are experiencing signs of degradation. Within Drujaygang Gewog alone, 81 water sources have been identified, 10 of

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which are in drying conditions (WMD, 2021). These trends signal an urgent need for evidence-based interventions to promote water sustainability. The Tarilum watershed, the only functional watershed serving the gewog, is especially critical as it is envisaged to support irrigation for 22 acres of wetland and 110 acres of dryland, as well as drinking water needs for the entire local population.

This assessment is part of the project "Adaptation to Climate-induced Water Stresses through Integrated Landscape Management in Bhutan", implemented by the Department of Water (DoW), Ministry of Energy and Natural Resources (MoENR). The study aims to provide a comprehensive assessment of the Tarilum watershed by identifying key issues, analyzing water quality parameters, measuring discharge, calculating availability, and projecting future water needs based on population trends to inform sustainable management practices.

Materials and Methods

Study Area

The Tarilum watershed covers a total area of 726.79 hectares with an altitude ranging from 418 to 1,788 meters above sea level (msl) and is located within the geographic range of 26.963091 °E|90.055298°N, 26.980389° E|90.043191°N, 26.956069°E|90.033603°N, and 26.971932°E| 90.022720°N. It lies within the administrative jurisdiction of Drujaygang Gewog under Dagana Dzongkhag.

The study site was selected due to its high importance as the only watershed supporting the gewog's irrigation and drinking water needs. With no alternative watersheds available, its protection is crucial for long-term water security. The gewog is increasingly impacted by developmental activities, particularly farm road construction, which threatens watershed health and integrity through erosion and landscape alteration. Furthermore, a number of drying water sources in the gewog have raised concerns about the future of water resources.

Land Use Land Cover (LULC) in the Watershed

The LULC in the watershed was analyzed using national LULC data (2016) in QGIS-3.34.0. The findings indicate the presence of diverse land use categories within the Tarilum watershed, among which the largest category of LULC was broadleaf forest, accounting for 50.51%, followed by Kamzhing (dryland) (25.22%) and shrubs (13.89%). About 5.22% of the watershed was covered by Chhuzhing (wetland), and 4.68% comprised orchards. The watershed's built-up area was only 0.47%, as shown in Table 1 and Figure 2.

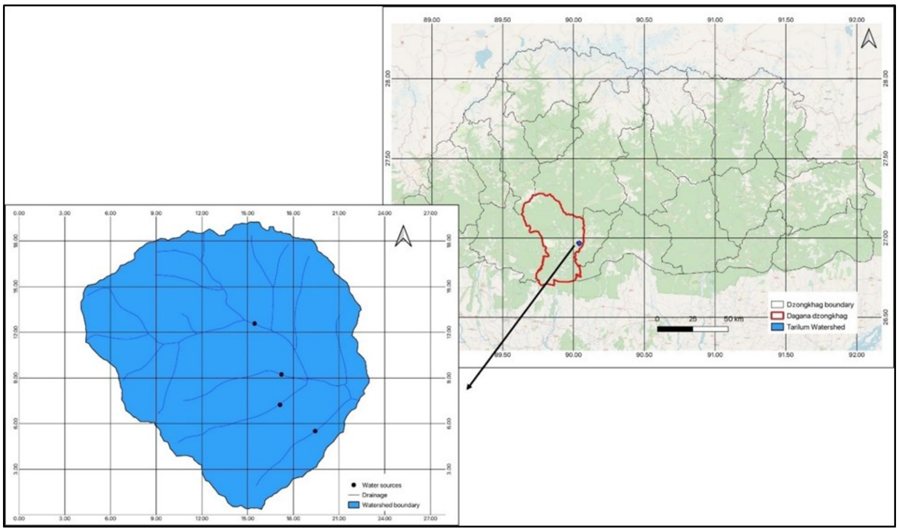

Figure 1: Study area

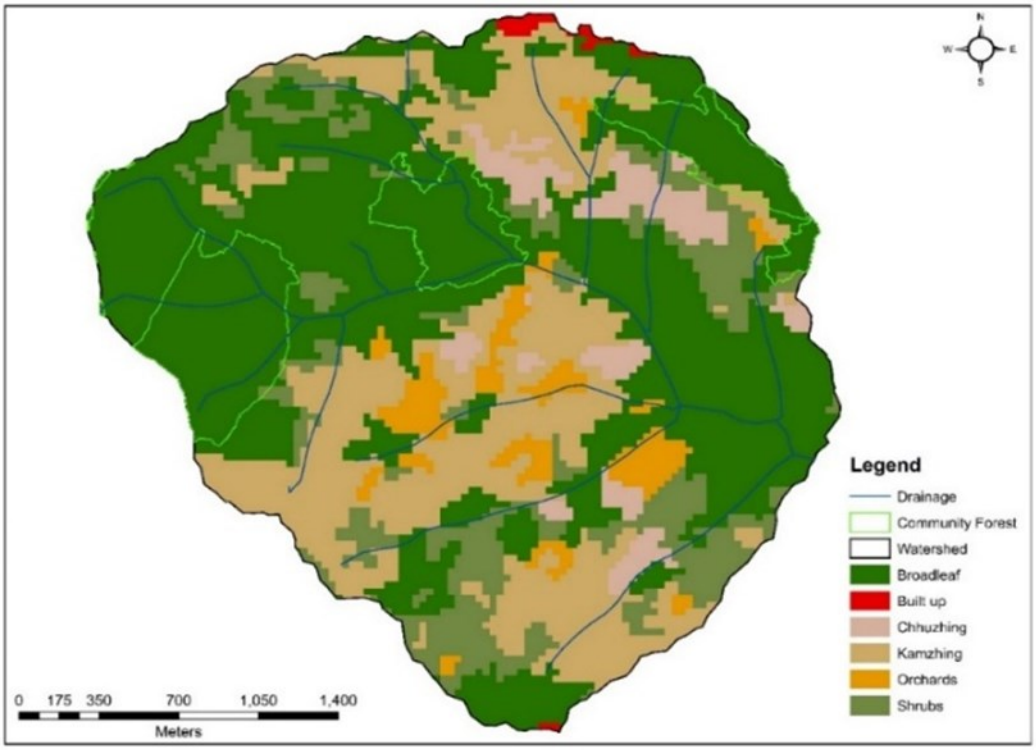

Figure 2: Land Use Land Cover (LULC) map

Table 1: Land Use Land Cover in the Watershed

Land Use Class	Area (ha)	Area (%)
Broadleaf	367.13	50.51
Built up	3.44	0.47
Chhuzhing (Wetland)	37.94	5.22
Kamzhing (Dryland)	183.29	25.22
Orchards	34.03	4.68
Shrubs	100.98	13.89

Watershed Condition Classification

The watershed condition classification was done considering up to 25 condition criteria from 28 predefined criteria in the national watershed classification guideline 2016 (annex 1), grouped into biophysical, socio-economic, climatic, and demographic categories (WMD, 2016), whereas the water use score was estimated based on the level of importance of the water source to the community's water use.

Using the following assessment formula (WMD, 2016), the condition score of the Tarilum watershed was calculated at 61% (details in Annexure 1), and the water use score was determined at "3" based on the level of importance (High Importance) of the watershed in sustaining the water requirements of the community.

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$$\%\ Condition\ Score = \left(\frac{Total\ Weighted\ Score\ of\ the\ criteria\ used}{Sum\ of\ Maximum\ Possible\ Score\ of\ the\ criteria\ used}\right) * 100$$

Potential Recharge Area Mapping

Hydrogeological mapping (Springshed approach) was used to map and delineate the potential recharge zones of the watershed using CorelDraw Graphics Suite-2021, the online platform www.earthpoint.us, and the Google Earth Pro interface (Kulkarni, 2019). The lithological data from the field were used to calculate the strike directions for geological mapping. Based on the geological principle of the perpendicular alignment of strike and dip direction, the strike direction's Fore Bearing (FB) and Back Bearing (BB) were calculated using the formula (Smith, 1922).

Fore Bearing (FB):

$$If\ Dip\ Direction\ (DD) > 90°, DD - 90, and\ if\ DD < 90°, DD + 90$$

Back Bearing (BB):

$$If\ FB\ > 180°, FB - 180, and\ if\ FB < 180°, FB + 180$$

The calculated strike directions along with the dip amount data were further processed using the online *www.earthpoint.us* interface before being imported to Google Earth for plotting. The entire dataset was plotted against their geographic coordinates (Figure 3), and the geological map of the watershed (Figure 4) was generated. The geological map was then used for the development of a 3D-conceptual hydrogeological layout of the watershed (Figure 5) that helps visualize the identification of the potential recharge areas in the watershed. The 3D layout was then referenced to the watershed boundary in Google Earth to demarcate the potential recharge area (Figure 8). This identified potential recharge area will be crucial in guiding the site selection process in the implementation of watershed management activities (Achu *et al*., 2020).

Future Demand Projections

Assuming a constant 2% annual population growth rate, consistent discharge from the water sources, and the total arable land area remaining the same, the compounded increase in water demand, inclusive of drinking, irrigation, and other domestic uses, was calculated using the following formula:

$$Population\ projection\ ('n'years) = \left(1 + \frac{r}{100}\right)^n$$

Where r is the rate of growth and n is the number of growth periods in years.

$$Domestic\ water\ requirement\ ('n'\ years) = (Projected\ Population\ in\ 'n'\ year)x(Per\ Capita\ LPD)$$

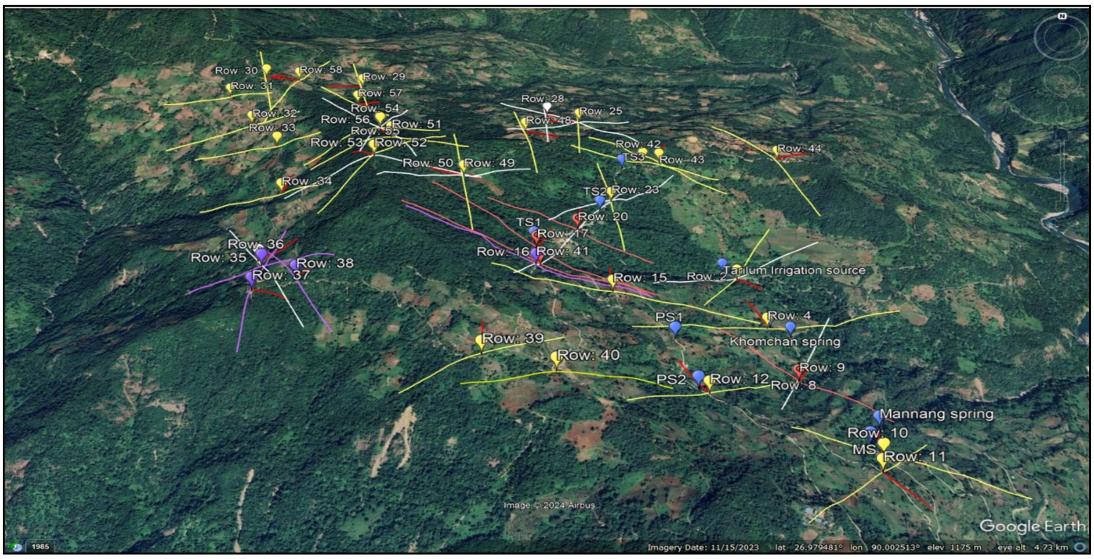

Figure 3: Plotting of field data

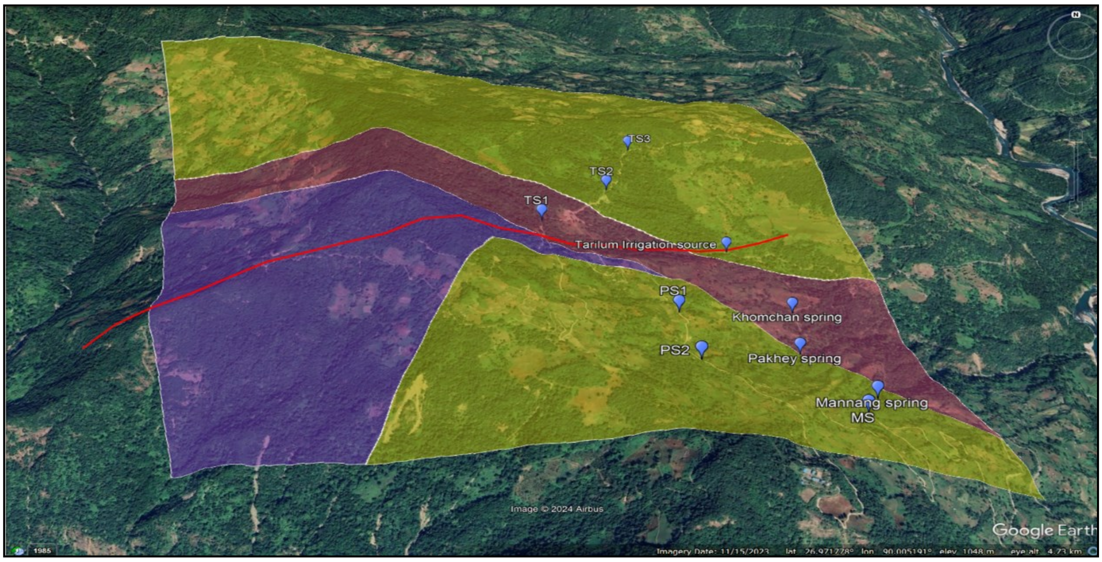

Figure 4: Geological map of the Tarilum watershed

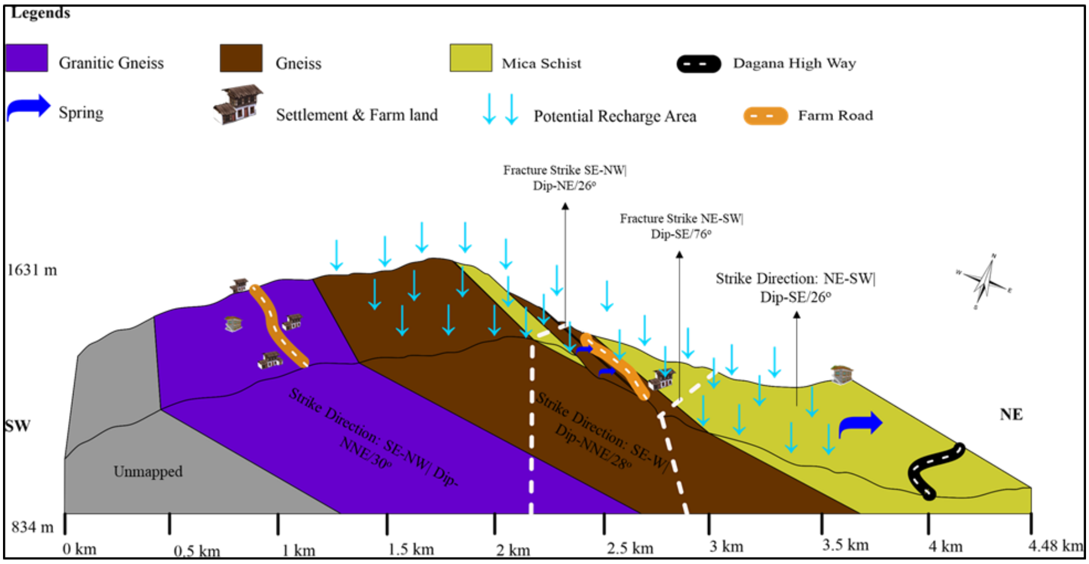

Figure 5: 3D-Hydrogeological conceptual layout of the watershed

Research Design

The study employed a mixed-methods study design combining quantitative and qualitative approaches (Creswell & Clark, 2017) to ensure comprehensive data collection and analysis to ascertain the current watershed condition for future management and monitoring. Specifically, a purposive sampling strategy was adopted for primary data collection involving field measurements of water discharge volumes and basic water quality parameters for every source in the watershed, while geological data involving rock measurements were collected along predefined transects, covering all accessible areas within the watershed (Palinkas *et al*., 2015; Ghimire *et al*., 2019; Seeger, 2007). Social data like demographic statistics, watershed issues, landholdings, etc., were gathered through participatory approaches, including focus group discussions (FGDs) and structured stakeholder meetings, ensuring that diverse community perspectives were comprehensively captured in the study.

Data Collection

Using GIS and Google Earth, the watershed boundary was predetermined based on hydrology and the existing water sources. The data on socio-economic condition, watershed issues, demographics, and land holdings were collected through consultation meetings with the gewog administration and FGDs with the community representatives of four chiwogs under the gewog.

The water discharge volume (Q) data were collected using an automatic magnetic flow meter (MF Pro: HACH-FH950.1), while the basic physical water quality parameters were collected using the handheld PCS tester-35 ENVCO Global. For potential recharge area mapping, lithological data comprising dip direction, strike, dip amount, and rock type were collected using devices (Figure 6), like a geological hammer, a geological compass (Brunton GEO Pocket transit, 0-360^{o} Scale), 10% Hydrochloric acid (HCL), Global Positioning System (Garmin GPS Map 65s), and a predesigned data recording sheet.

Data Analysis

A multi-method analytical framework was employed to assess the hydrogeological and water resource characteristics of the Tarilum watershed. Lithological data were cleaned and organized in Excel and then mapped using CorelDRAW Graphics Suite 2021 to generate the 3D-hydrogeological layout of the study area and to help demarcate potential recharge zones. Water quality and quantity parameters were analyzed in *Jamovi 2.6.44* through descriptive statistics, non-parametric testing, and Principal Component Analysis (PCA) to evaluate spatial variation and inter-parameter relationships. Watershed classification and categorization followed the national Watershed Classification Guideline (2016), while future water demand was projected using the compound interest formula, based on current water availability, a 2% annual population growth rate, and a fixed per capita water consumption rate. QGIS tools were employed for topographical assessments of the watershed, including aspect, elevation, and slope analysis, to complement the hydrogeological evaluation.

Results and Discussion

Watershed Condition Category

The combined result, determined through cross-tabulating (Figure 7) the condition and

Figure 6: Data collection equipment

use score, categorizes the watershed into the "Degraded category". This indicates an immediate requirement for management interventions before its condition becomes irreversible, to ensure a sustained supply of water to the communities that are dependent on this watershed. Its criticality for effective management is further substantiated by the absence of other watersheds, while there is an anticipation of growth in the amount of water required with the increasing population.

The statistical analysis of the five water quality parameters (Table 3), which include pH, electrical conductivity (EC), total dissolved solids (TDS), salinity, and temperature, across the four sampling locations revealed relatively low variability. The mean pH was 7.67 (SD = 0.05), indicating neutral to slightly alkaline water across all sites. EC reported an average of 88.60 µS/cm, with the highest value being recorded at Khomchan Chu (102 µS/cm), suggesting low mineralization (Hem,1985).

		water use rating		
		1	2	3
Condition score	< 50%	PRISTINE	PRISTINE	NORMAL
	50 - 75%	PRISTINE	NORMAL	DEGRADED
	> 75%	NORMAL	DEGRADED	CRITICAL

Figure 7: Watershed classification matrix (2016 Watershed classification guidelines)

Potential Recharge Area

The findings (Figure 8) indicated that recharge areas were geographically distributed mostly above the water sources, and some parts of the potential recharge areas extended beyond the delineated watershed boundary, indicating the importance of holistic management of the watershed at a landscape level.

Water Quality

The five basic water quality parameters for four water sources in the watershed (Table 2) were measured and recorded for analysis. Their statistical analysis was conducted using the *Jamovi 2.6.44* software.

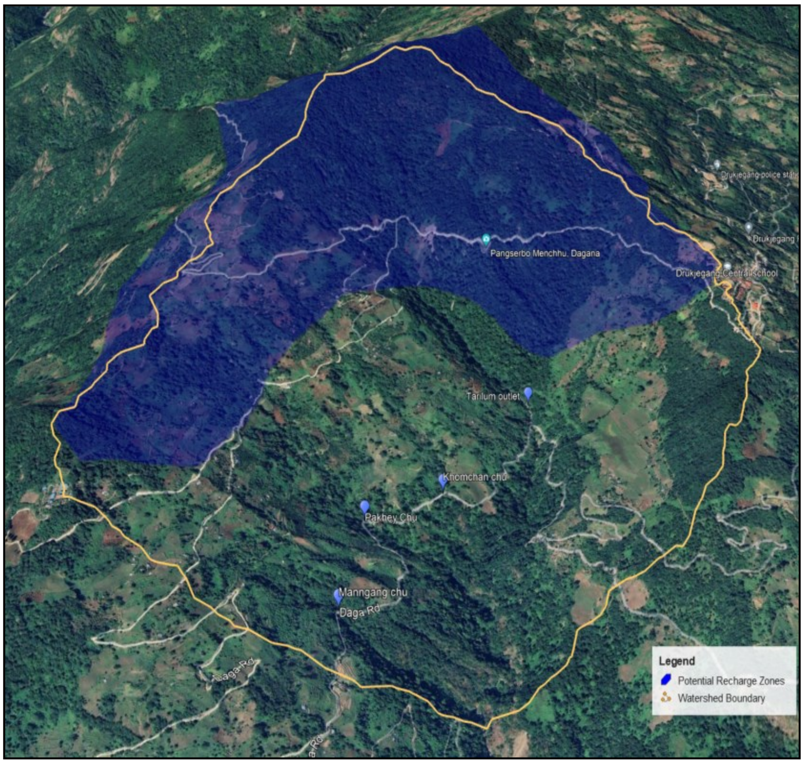

Figure 8: Identified potential recharge area for water sources in the watershed

Table 2: Physical water quality parameters recorded on-site

Name	Easting	Northing	Quality Parameters				
			pH	EC (µS/cm)	TDS (ppm)	Salinity (ppm)	Temp (°C)
Tarilum Chu	90.0428	26.9704	7.7	83.8	59.1	39.6	16
Khomchan Chu	90.0458	26.9649	7.6	102	71.8	48.2	17.6
Pakhey Chu	90.0456	26.9615	7.7	91.6	64.8	43.4	15.5
Mannang Chu	90.0495	26.959	7.7	77	54	36.5	14.5

TDS and salinity followed similar patterns, averaging 62.42 mg/L and 41.92 ppm, respectively, and remained well below threshold values for potable use (Cotruvo, 2017). Temperature varied slightly across sites, with a mean of 15.90°C.

The data visualized using the box plots (Figure 9) further confirmed the consistency and homogeneity of water quality within the watershed since it didn't show any extreme outliers, except for the pH; however, all values are clustered around neutral to slight alkalinity, indicating no significant spatial differences in acidity.

Statistical differences among the four sampling sites were evaluated using non-parametric Kruskal-Wallis tests (Table 4). The results indicated no statistically significant differences in any of the measured parameters ($\chi^2 = 3.00$, df = 3, $p = 0.392$ for all variables), suggesting a high degree of homogeneity in water quality within the watershed. This uniformity may be likely linked to similar topographical, geological, and land use characteristics across the sampled points.

Table 3: Descriptive Statistics of Physical Water Quality Parameters

Physical Quality Parameters	N	Missing	Mean	Median	SD	Minimum	Maximum
pH	4	0	7.67	7.7	0.05	7.6	7.7
EC (µS/cm)	4	0	88.6	87.7	10.74	77	102
TDS (ppm)	4	0	62.42	61.95	7.65	54	71.8
Salinity (ppm)	4	0	41.92	41.5	5.05	36.5	48.2
Temperature (°C)	4	0	15.9	15.75	1.29	14.5	17.6

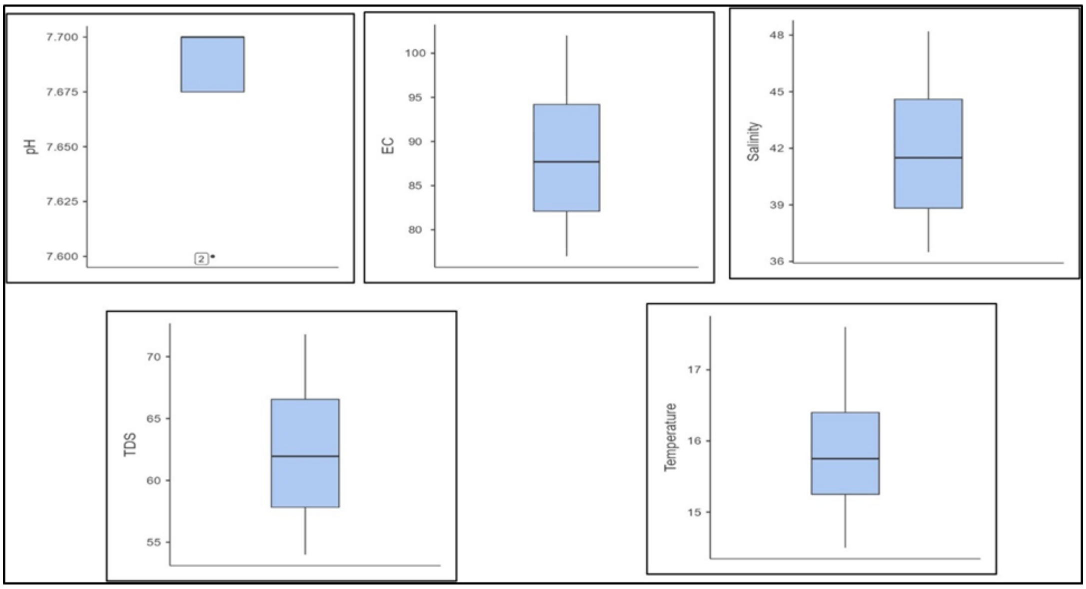

Figure 9: Box Plots for Physical Water Quality Parameters

Principal Component Analysis (PCA)

To identify underlying relationships among water quality parameters, Principal Component Analysis (PCA) with varimax rotation was conducted. The analysis extracted one principal component with an eigenvalue of 4.62, explaining 92.34% of the total variance (Table 6). This indicates that one main underlying factor explains most of the variation in the data.

Table 4: Kruskal-Wallis Test

Parameters	**χ^2**	**df**	**p**
pH	3.00	3	0.392
EC	3.00	3	0.392
TDS	3.00	3	0.392
Salinity	3.00	3	0.392
Temperature	3.00	3	0.392

Table 5: Principal Component Analysis

Component loadings		
Parameters	**Component 1**	**Uniqueness**
pH	-0.9	0.18
EC	0.99	0.03
TDS	0.98	0.04
Salinity	0.98	0.03
Temperature	0.95	0.1

Note: 'varimax' rotation was used

This component showed high positive loadings (Table 5) for EC (0.99), TDS (0.98), salinity (0.98), and temperature (0.95), with a strong a negative loading for pH (-0.90). These results suggest that these physical parameters are closely interlinked, likely reflecting a common geochemical influence such as dissolved ionic concentration. The relatively high uniqueness of pH (0.18) indicates that, although related, it behaves somewhat independently, possibly due to buffering effects or local biological factors.

Water Quantity

The Tarilum watershed comprises four perennial streams (Table 7), with Tarilum Chu being the primary source, contributing approximately 69.3% of the total discharge. The total cumulative flow from the watershed in February was measured at 41.749 litres per second (LPS), translating to 3.61 million LPD. Among other sources, Pakhey Chu provided 9.6 LPS (23%), while Khomchan Chu and Mannang contributed a marginal flow of 1.619 LPS (3.9%) and 1.6 LPS (3.8%), respectively. These figures indicate that the water availability for the proposed irrigation project is heavily reliant on the Tarilum Chu.

Table 6: Summary of Principal Component Analysis

Component	SS Loadings	% of Variance	Cumulative %
1	4.62	92.34	92.34

this correlation is not statistically significant at the 0.05 level, likely due to the small sample size (n = 4).

Current Water Demand

With the existing population of 170 people, a total water of 22,950 LPD was estimated to

Table 7: Recorded Water discharges (Q) from different sources in the watershed

Location Name	Easting	Northing	Altitude	Q (LPS)	Q (LPD)
Tarilum Chu (main source)	90.0428	26.9704	800	28.93	2499552
Khomchan Chu	90.0458	26.9649	749	1.619	139882
Pakhey Chu	90.0456	26.9615	738	9.6	829440
Mannang	90.0495	26.959	700	1.6	138240
Total				41.749	3,607,114

A bar chart (Figure 11) below presents the different percentages of flow contributions from different sources to the overall flow from the watershed.

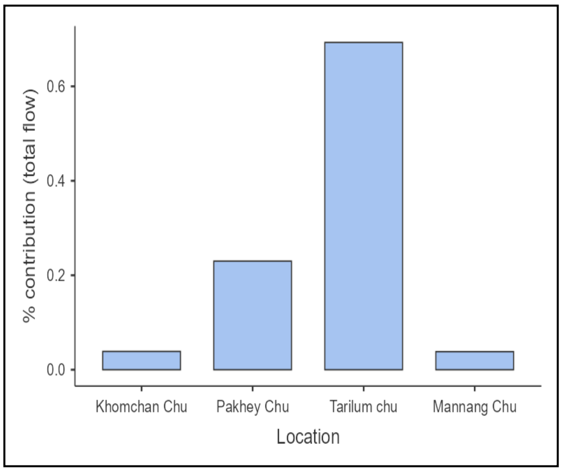

Figure 11: Discharge (% contribution)

The data showed that the discharge volume tends to increase with increasing elevations (Figure 12). The Pearson correlation coefficient between discharge and altitude was 0.87, indicating a strong positive relationship. However, the p-value of 0.131 suggests that

required for drinking at present considering the per capita per day water requirement at 135 LPD (NEC., 2008), while a total irrigation water requirement was calculated at 0.245 million LPD based on the total wetland area of 22 acres, thereby summing up to the overall water requirement of approximately 0.268 million LPD (Table 8). This was

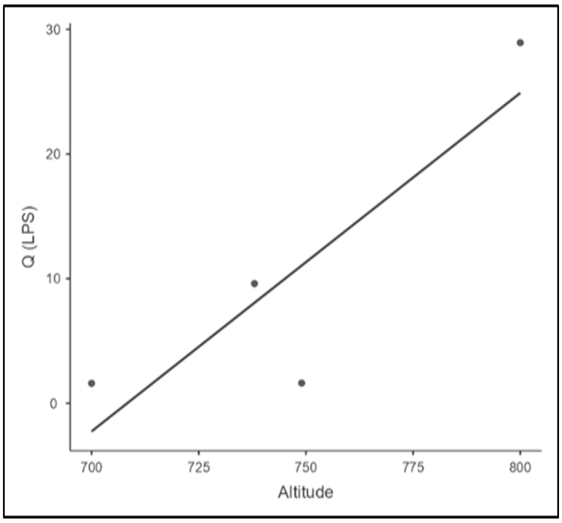

Figure 12: Linear Correlation (Discharge vs Altitude)

was estimated based on the existing water requirement of 0.32 l/s/ha (or 0.129 l/s/acre) in Dagana Dzongkhag in February for irrigation purposes (NECS & DoA, 2016), indicating that, to irrigate one acre of land, 11,193.522 LPD is required. However, it should be noted that water requirement is dependent on the season and the type of crops being grown (Biemans et al., 2016; NECS & DoA, 2016), and the discharge data will also vary accordingly (Hoekstra *et al*., 2012).

Slope

Slope analysis was carried out using the Digital Elevation Model (DEM). Shuttle Radar Topography Mission (SRTM) revealed diverse slope gradients across the watershed. Most of the watershed areas exhibited a gradient of 25 degrees or less (Figure 13). However, in a few pockets of the catchment area, a gradient of more than 35 degrees was observed, indicating their vulnerability to rapid surface runoff, sediment transport, and downstream erosion.

Future Demand Projections

Projections up to the year 2054 indicate that the total water demand, estimated at approximately 531,977 LPD, including both drinking and irrigation needs, can be adequately met by the current water discharge capacity of 3,607,114 LPD (Table 9). This suggests that, under stable discharge and land-use conditions, the Tarilum watershed is capable of sustaining the projected population and agricultural water needs of the Gewog for the next 30 years.

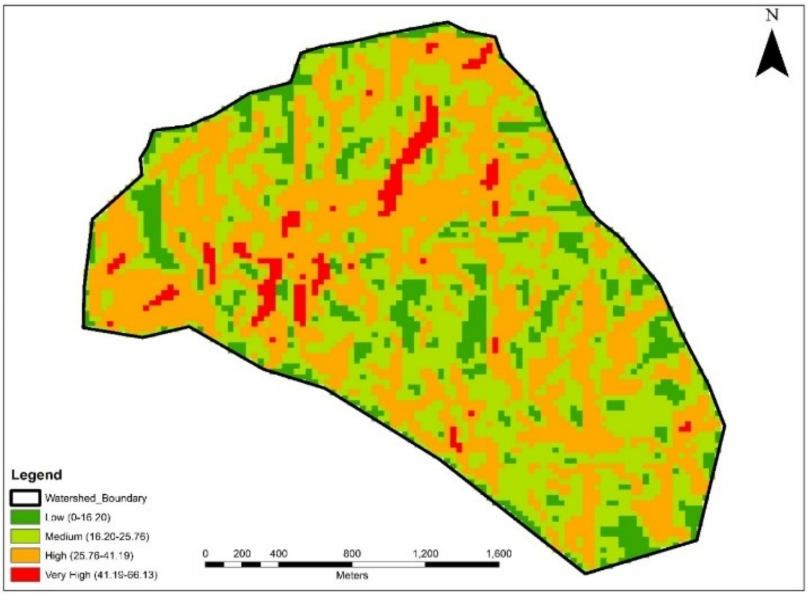

Figure 13: Slope analysis map of the Tarilum watershed

Table 9: Current and Projected Water Demands

Q(LPS)	Q (LPD)	Current Requirement		Projections		
		Drinking (LPD)	Irrigation (LPD)	Drinking (LPD)	Irrigation (LPD)	Total (LPD)
41.79	3,607,114	22,950	245203	41570.8	245203	286774
Total		268,153.20		531,977.15		

Topographical Characteristics Influencing Hydrology

Three topographic features (slope, aspect, and elevation) that play a critical role in hydrology were analyzed to understand the sustainability of water resources in the watershed.

Aspect

The results of the analysis showed a heterogeneous distribution of slope orientations in the Tarilum watershed. The north-facing slopes were more prevalent in the watershed, accounting for more than 50% of the watershed area, which was mostly distributed in the West and Southwest parts. In contrast, analysis revealed a considerable amount of watershed areas with a south-facing slope in the East and Northeast parts of the watershed (Figure 14). In the northern hemisphere, north-facing slopes tend to have more distinct vegetation, cooler temperatures, lower evapotranspiration rates, and damp soils that help in water infiltration since they receive less solar radiation than the south-facing slopes.

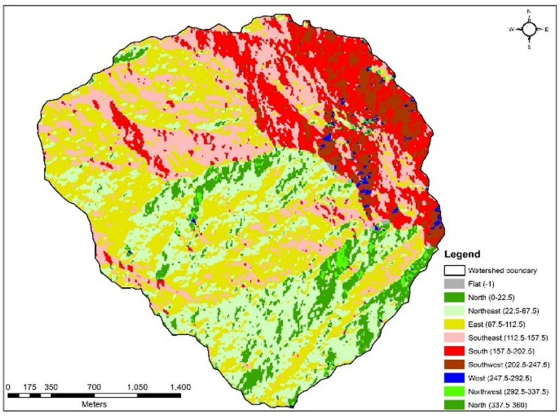

Figure 14: Aspect analysis of the watershed

Elevation

Based on the results of the elevation analysis using the DEM, most of the watershed areas have an elevation of less than 1000 msl. The elevation in this watershed ranged from 418 msl in the southeast to 1788 msl in the northwest parts of the watershed area (Figure 15). These high-elevation areas in the northwest of the watershed were found to be critical headwaters for this watershed since they have the highest forest cover with minimal anthropogenic interferences.

The statistical analysis of the topographical characteristics was constrained by the unavailability of time-series climate data and baseline reference datasets, owing to the absence of prior studies within the watershed. A comprehensive examination of these variables and their influence on the hydrological cycle, particularly regarding local watershed dynamics and water resource management, necessitates further research and investigation.

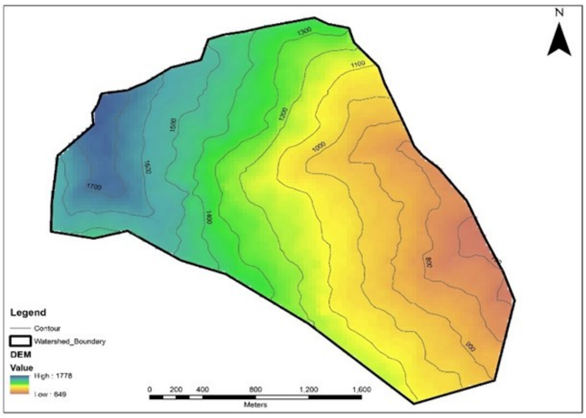

Figure 15: Elevation analysis in the watershed

Conclusion

The ecological integrity of the watershed is essential for maintaining its hydrological services, but most of the watershed is disturbed and is currently classified in the "Degraded category" due to a combination of anthropogenic pressures, including deforestation, unsustainable agricultural practices, and land-use changes contributing to erosion and disturbances in natural recharge pathways.

Despite the watershed's current ability to supply potable water, the presence of highly porous recharge zones and steep terrain elevates its vulnerability to degradation. These conditions necessitate the implementation of targeted land and water management strategies. Potential interventions include the implementation of stone-faced bench terracing or raised bunds on moderately steep agricultural slopes to reduce soil erosion and enhance slope stability. This type of terracing is particularly suited to the site's topography and existing dryland cultivation practices.

In addition, the establishment of riparian buffer zones using native grasses and shrubs is recommended to minimize surface runoff and sedimentation into streams. Reforestation of critical groundwater recharge zones with deep-rooted indigenous tree species is also proposed to improve infiltration and mitigate further land degradation.

Future research should prioritize the quantification of groundwater recharge dynamics, evaluation of long-term land-use changes on watershed hydrology, and simulation of climate change scenarios to inform adaptive water resource management. Additionally, field-based studies assessing the effectiveness of specific intervention measures, such as terracing, buffer zones, and reforestation, in comparable ecological settings would strengthen the practical relevance of this study and contribute to more robust, evidence-informed policy and planning.

Acknowledgments

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Annexure 1: Scoring Sheet for Watershed Assessment and Classification

	TIER	**SCORES**			**COMMENTS**
	Tier 1 Basin				Stream name: Tarilum Chu
	Tier 2 Sub-Basin	GPS Coordinates (DD)			Village/Geog/Dzongkhag: Drujeygang, Dagana
	Tier 3 Watershed	N:26.97036/E:90.04275			Assessor: DoW Team
	Discharge: 28.93 LPS (major source only)				Elevation (m): 800
Commentary on water use: Irrigation & Drinking		Date:9/02/2024			
Condition assessment Criteria		**Score**	**Weighting**	**Weighted Score**	
Water quality sample collected?		No			
BIOPHYSICAL					
Erosion	Gully erosion	2	1	2	
	Rill/Sheet erosion	2	2	4	
	Mass movements/ landslide	2	2	4	
	Debris flows	2	3	6	
W/ Quality	Turbidity		0	0	
	Eutrophication	1	1	1	
	Salinity	1	3	3	
	pH	1	3	3	
Forest coverage		2	2	4	
Riparian vegetation (30m on both banks)		2	2	4	
Natural wetlands		3	2	6	
SOCIO-ECONOMIC					
Settle.	% of watercourse close to a settlement	2	1	2	
	Sewering of houses	2	1	2	
Industrial use		1	2	2	
Agriculture	Irrigation	2	2	4	Aibumthang Chewog/Yyangsebji/ Krontoed Villages
	Extent of farmland	3	2	6	
	Degraded arable land	1	1	1	
	SWC measures	2	2	4	

	Use of pesticides/herbicides/fertilizers	3	2	6	Used for oranges, vegetables, fodder, and weedicides
Livestock density		2	1	2	Total estimate: 150-200
Grazing		2	1	2	
Mining Activities		1	2	2	
Forest Activities		1	2	2	
Roads (density and condition)		3	3	6	
Man-made change in watercourses		1	2	2	
Incidence of forest fires		1	2	2	
CLIMATIC					
Precipita-tion		3	2	6	2500-3000 mm/year
DEMOGRAPHIC					
Population density/rural/urban		2	2	4	Total estimate: 2000
	Total weighted score	50		92	
	Maximum score			150	
	% score	61%			
	Water use score	3			
Overall Risk Score		Degraded			