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REVOLUTIONIZING CIVIL ENGINEERING WITH GEOINFORMATICS AND AI FOR SUSTAINABLE DEVELOPMENT

GIS and AHP-based methods for river risk zone (RRZ) assessment: a case study of the Himalayan rivers in Doon Valley, Uttarakhand, India

Ashish Mani[1,2] · Maya Kumari[1] · Ruchi Badola[2]

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Abstract
Pollution from both point and non-point sources, over-extraction of freshwater, and significant climatic changes in recent years are some factors that put substantial pressure on worldwide water resources. As the demand for potable water increases globally for human, agricultural, and industrial uses, the need to evaluate the river risk assessment also increases. GIS-based studies in recent years have gained prominence as they are rapid, cheap, and provide insight into the resources for further development of research on the rivers. Therefore, the present study assessed the river risk zone (RRZ) of the Himalayan rivers in the Doon Valley of Uttarakhand in India. A combination of GIS and analytical hierarchical process (AHP) techniques was used in the present study. A total of 15 thematic layers, total dissolved solids (TDS), conductivity, pH, salinity, temperature, depth, drainage density, land use/land cover (LULC), elevation, slope, flow, width, soil type, geology, and aspect, were prepared and studied from primary survey data and open-source digital elevation model (DEM) and satellite imagery for RRZ evaluation. Weights assigned to each class are based on their characteristics and risk towards the river through the AHP method. The RRZ map thus obtained was categorized into five classes: very high, high, medium, low, and very low. The study reveals that about 56.38% of the river area is covered under high and very high-risk zones. The medium, low, and very low-risk zones are observed in 33.71%, 2.93% and 6.98%, respectively. Identifying and monitoring these risk zones give planners and decision-makers opportunities to intervene where it counts most to prevent further degradation or collapse systematically, thus preserving the health and sustainability of river systems over time.

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✉ Ashish Mani
ashish.mani@s.amity.edu

Maya Kumari
mkumar10@amity.edu

Ruchi Badola
ruchi@wii.gov.in

1 Amity School of Natural Resources and Sustainable Development, Amity University, Sector-125, Noida 201313, Uttar Pradesh, India

2 Ganga Aqualife Conservation Monitoring Centre, Wildlife Institute of India, Chandrabani, Dehradun 248001, Uttarakhand, India

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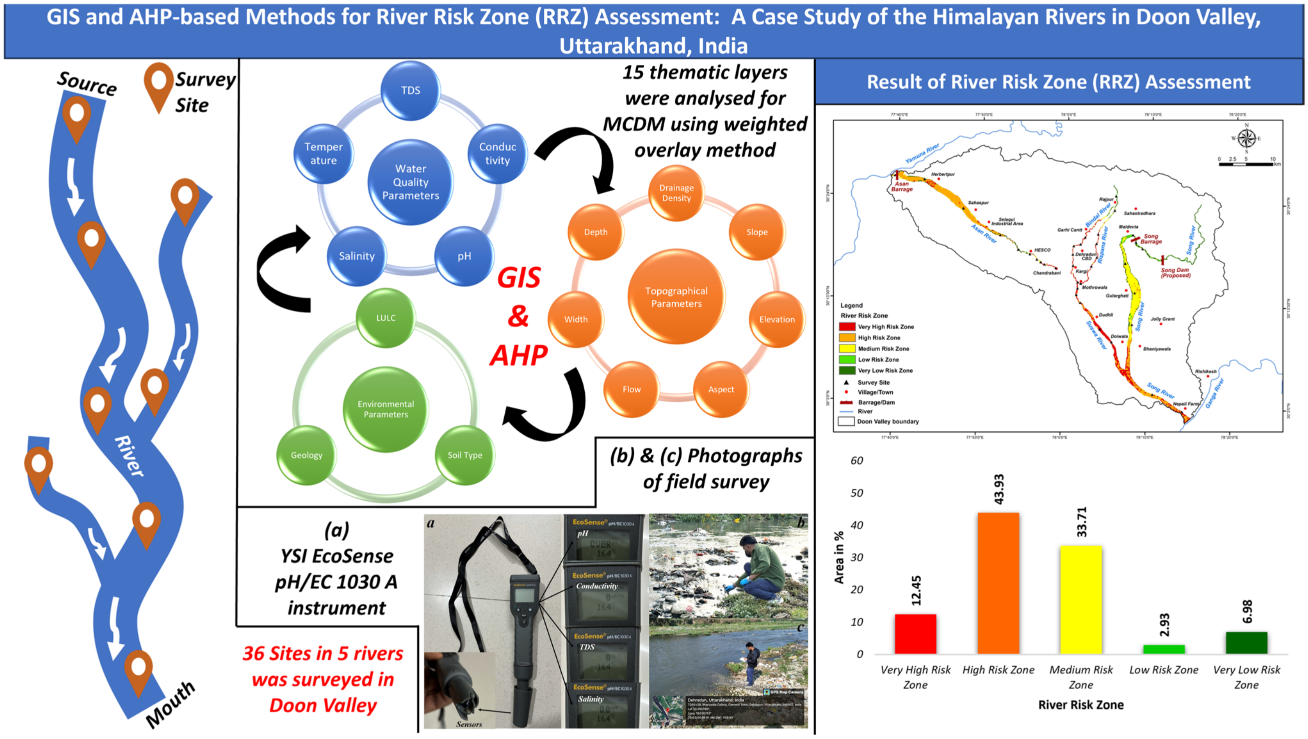
Graphical Abstract



Keywords AHP · GIS · River risk zone · Doon Valley · Water quality · Topography · Environment · Himalayan rivers

Introduction

River risk zone (RRZ) assessment has gained prominence due to increasing global pressure on freshwater resources (Grill et al. 2019). River ecosystems are undergoing multiple stressors, such as pollution from industrial and agricultural activities, habitat fragmentation, and climate change (Poff et al. 1997; Palmer et al. 2010). Assessing risks to the river systems is vital for understanding the impacts of human activities, climate change, and natural processes on water quality and river health (Palmer et al. 2009). Integrated methods considering water quality, topographical, and environmental parameters are essential for effective RRZ assessment, as they provide a holistic understanding of the factors affecting river health and resilience (Liu et al. 2016; Zeleňáková et al. 2021).

Water quality parameters are fundamental in evaluating the health of a river system from both point and non-point sources of pollution. These parameters are temperature, pH, total dissolved solids, conductivity, and salinity. Temperature is a critical parameter affecting aquatic organisms' physiological activities, rates of biochemical reactions, and solubility of gases and salts in water (Bal et al. 2021). pH, a measure of the hydrogen ion concentration, affects chemical constituents' solubility and biological availability, such as nutrients and heavy metals (Namieśnik and Rabajczyk 2010). Total dissolved solids (TDS) address the total impurities present in a solution. Such impurities usually include some dissolved organic substances present in water as well as many inorganic salts like bicarbonate, chloride, sodium, potassium, magnesium, and sulphate (Wang 2021). Conductivity refers to the impaired nature of water when conducting an electric current and is related to the salts in a given solution, which can suggest pollutants within the water. Salinity is the term used to define the number of salts dissolved in water, which can significantly affect the health of aquatic ecosystems (Cañedo-Argüelles et al. 2019).

On the other hand, environmental parameters cover comprehensive aspects of river-defining factors like land use/land cover (LULC), hydrology, topography, geology, and soil type. Human activity in land use land cover, such as urbanisation, deforestation, and agricultural practices, adversely impacts the hydrological regime and pollutes the river systems (Mani et al. 2023a, b, c). Hydrological parameters, such as flow regime, river depth, and main channel width, are crucial for maintaining the ecological integrity of river systems and supporting diverse biological communities (Dutta et al. 2017). Topographic parameters such as slope, elevation, aspect, and drainage density are essential for analysing surface water modelling (Mani et al. 2022). Geology influences the natural background levels of minerals and metals in rivers and affects the buffering capacity of water bodies against acidification (Mandal et al. 2024). Soil type impacts the water infiltration rate through its pores (Mani et al. 2024).

The advent of advanced monitoring technologies and geographic information systems (GIS) has facilitated the collection and analysis of data for RRZ assessment. Remote sensing technologies, such as satellite imagery and drones, enable monitoring land use changes, vegetation cover, and topographical and hydrological alterations over large spatial scales and at high temporal resolution (Singh et al. 2014). GIS tools allow for the integration of diverse datasets, including water quality measurements, land use maps, and climatic data, to model the spatial distribution of risks across river landscapes (Mani and Kumar 2020). The analytical hierarchy process (AHP) is an effective tool for dealing with complex decision-making in multi-criteria fields, and it was introduced by Thomas Saaty (1980). The tool helps reduce complex decisions to a series of pair-wise comparisons and then synthesise the results. Also, the AHP tool is an adequate method for assessing the consistency of the result, consequently reducing the bias in the decision-making process. These technological advancements have significantly enhanced the capacity to conduct comprehensive RRZ assessments and multi-criteria decision-making for river management and conservation.

Recent studies have underscored the significance of combining water quality, topographical and environmental parameters in RRZ assessment. Bozdağ (2015) used GIS and AHP methods to evaluate the irrigation water quality in the aquifers of Cumra Irrigation District (CID). Nine parameters were analysed. Their study found that irrigation water quality is highly suitable for irrigation purposes. Yang and Wang (2020) proposes a stochastic cloud-based MCDM framework for river health assessment, addressing uncertainties in performance values and criteria weights. Combining stochastic multi-criteria acceptability analysis (SMAA), grey correlation analysis, and TOPSIS, it improves evaluation accuracy and reliability, demonstrating its effectiveness in Taihu Basin for better river management and decision-making. Saha and Paul (2021) developed an efficient development plan for a heavily industrialised, densely populated, planned, and severely polluted metropolis using the GIS and AHP-based integrated model to find locations ideal for water use. The multi-purpose water quality index (WQI) and Ryznar suitability index (RSI) were computed by analysing the physicochemical properties of the surface and groundwater of the strategic places. In another research, the new ecological susceptibility index (ESI) was prepared for the Mayurkashi River using AHP and GIS techniques (Ghosh and Maiti 2021). Mishra et al. (2022) used the GIS and AHP methods to understand the physico-chemical and microbiological characteristics of the Asan River. A total of fourteen water quality parameters were analysed from seven locations. They found that the Asan River is highly polluted near its upper stretch. They found that the middle stretch of the river is under ecological stress. The article by Shikhteymour et al. (2023) presents a multi-criteria decision-making and machine learning strategy to evaluating flood risk in Abarkuh County, Iran. With 6% of the area at high risk, it uses support vector machine (SVM) to identify the main flood hazard variables and susceptibility influences, offering a framework for flood management in dry and semi-arid regions. Das (2023) integrates information entropy, GIS, and multi-objective decision-making tools (TOPSIS, ELECTRE) to assess the Mahanadi River's water quality. Using multivariate analyses, principal component analysis (PCA), cluster analysis (CA), and discriminant analysis (DA), it identifies pollution levels across 19 locations, with leaching, pollutants, and wastewater as key contributors, aiding water quality management. These studies underscore the need for multidisciplinary approaches in RRZ assessment, where physical water quality parameters are evaluated with environmental parameters to identify and mitigate risks effectively.

Despite the advancements made in the assessment of the RRZ, some problems concerning the water quality, topographical, and environmental parameters remain. Rivers are unstable systems that can be affected by different factors, and these relations can be complex and variable. For instance, how land use changes affect water quality may be land-use-specific, soil-specific, and even climate-specific. Similarly, changes in flow regimes and their effect on river ecosystems may also depend on species and historical flow patterns (Vannote et al. 1980). Addressing these complexities requires interdisciplinary research and adaptive management approaches that can account for the variability and uncertainty inherent in river systems. The novelty of this study lies in its integration of GIS and AHP to assess the Doon Valley River risk zones (RRZ). By evaluating 15 water quality, topographical, and environmental factors, it provides a comprehensive and cost-effective method for river risk management and preservation. Further, this RRZ assessment will be a solution for understanding and managing the health of river ecosystems and will enable the identification of risks and the development of targeted management strategies.

Materials and methods

Study area

The study area consists of the five major rivers of Asan (~40 km), Bindal (~23 km), Rispana (~27 km), Song (~80 km), and Suswa (~21 km) in the Doon Valley, situated between Shiwalik and Lesser Himalaya mountain ranges, in Uttarakhand (Fig. 1). It is located between 77°38′E to

78°20′E and 30°01′N to 30°28′N. Dehradun, Mussoorie, Herbatpur, Selaqui, Doiwala, and Rishikesh are some of the main cities in the study area. The Asan River flows west to join the Yamuna, while the remaining four all flow east into the Ganga (Mani et al. 2023a, b, c). These rivers are of great ecological importance in the Doon Valley, sustaining the valley's vegetation. The total combine area of the riverscpae for these rivers is 80.63 km^2. Currently, they are under severe pressure from the municipality regarding waste disposal, sewage treatment and sewage discharge, unregulated tourism, illegal sand mining, water extraction, and agricultural expansion. Urbanization has gone hand in hand with rising levels of stress in the rivers, resulting in temperature increases and urban heat waves across Doon Valley (Mani et al. 2021). The study area has a total annual rainfall of approximately 2000 mm, and the average temperature varies from 1 °C in winter to 43 °C in summer. The main channels of the rivers are narrow and have widths of about 2 to 3 m in the pre-monsoon season. However, during the monsoon and post-monsoon periods, these channels widen as they extend into the river floodplain, contributing to urban flooding in the area (Dwivedi et al. 2024).

Data and methods

This paper utilises GIS and AHP techniques to assess the risk zones in the Doon Valley rivers through water quality and environmental factor analysis, incorporating 15 layers of information, including total dissolved solids (TDS), conductivity, pH, salinity, temperature, depth, drainage density, land use/land cover (LULC), elevation, slope, flow, width, soil type, geology, and aspect.

The primary data of water quality and environmental factors, which included TDS, conductivity, pH, salinity, temperature, depth, flow, and width, were obtained using the YSI EcoSense pH/EC 1030 A instrument during the field survey at 36 sites across five rivers (Asan, Bindal, Rispana, Song, and Suswa) in 2022 and 2024 (Fig. 2). The mean values of these parameters from both years were calculated and used to analyse their spatial distribution (Table 1). An inverse distance weighted (IDW) interpolation method using ArcGIS Desktop software 10.6.1 was employed to interpolate these values and visualise their spatial distribution across the study area. This study represents the highest number of sites surveyed in the Doon Valley rivers for the water quality analysis.

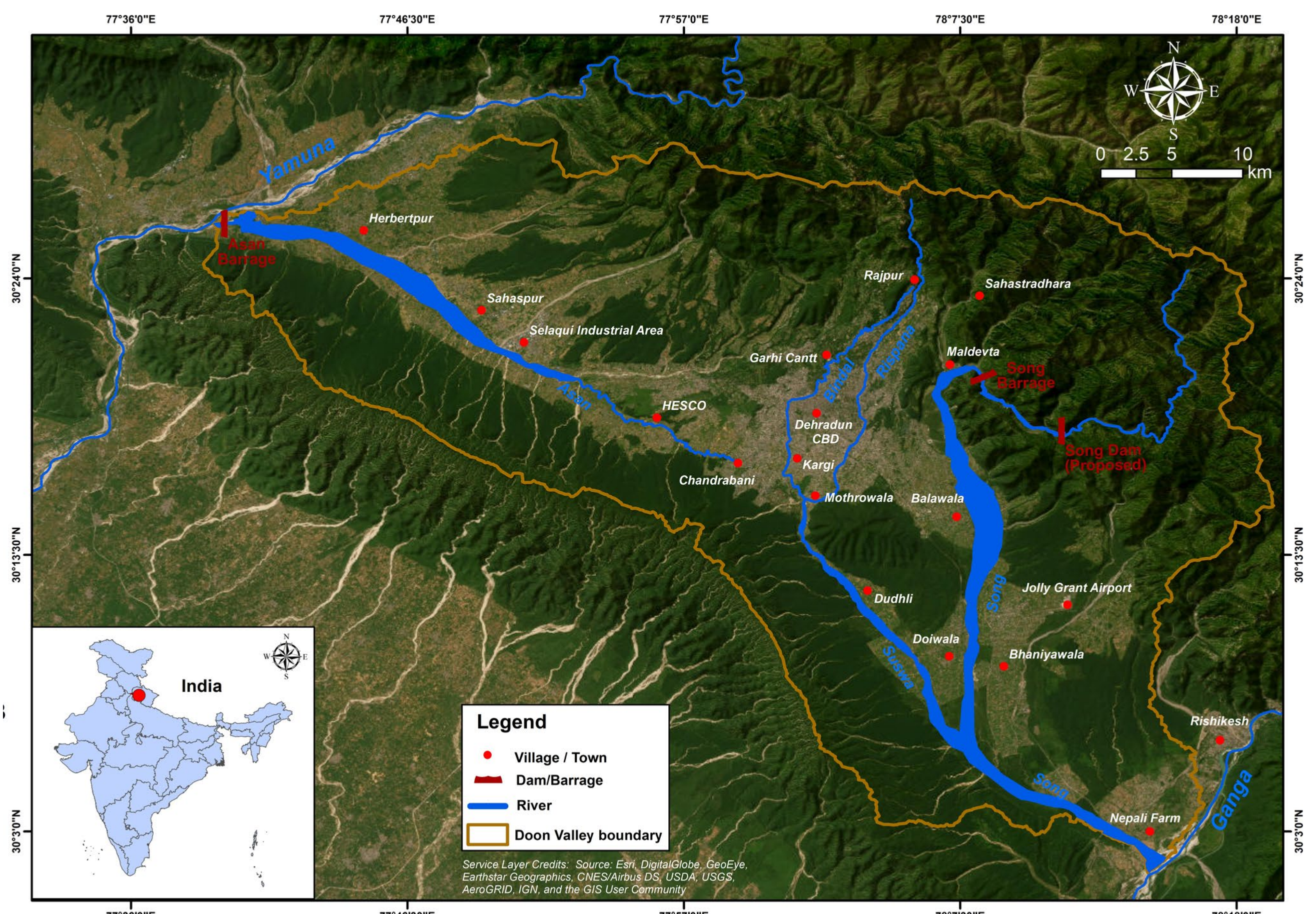


Fig. 1 Study area map of the Doon Valley rivers

The pre-processing analysis of other environmental datasets of the Doon Valley rivers was carried out using advanced GIS and remote sensing software. The Shuttle Radar Topographic Mission (SRTM) 30 m resolution data was used to evaluate the topographical factors: slope, elevation, aspect, and drainage density, with the support of Spatial Analysis Tools (SATs) in ArcGIS desktop software 10.6.1.

The Sentinel 2 satellite data at 10 m resolution was used to prepare LULC classification. The supervised classification method used the maximum likelihood (ML) classifier in the ERDAS Imagine software version 2016 for LULC classification. The overall accuracy and kappa coefficient were calculated using the 90 training samples from the six LULC classes (built-up, agricultural land, forest area, wasteland, dry riverbed, and waterbodies). User's accuracy, producer's accuracy, overall accuracy (OA), and kappa coefficient (k) are mentioned in Eqs. 1, 2, 3, and 4. The kappa coefficient rating criteria is in Table 2 (Islami et al. 2022).

$$User's\ Accuracy = Number\ of\ Correctly\ Classified\ Pixels\ in\ each\ Category / Total\ Number\ of\ Reference\ Pixels\ in\ that\ Category\ (The\ Row\ Total) \quad (1)$$

$$Producer's\ Accuracy = Number\ of\ Correctly\ Classified\ Pixels\ in\ each\ Category / Total\ Number\ of\ Reference\ Pixels\ in\ that\ Category\ (The\ Column\ Total) \quad (2)$$

$$Over\ all\ Accuracy\ (OA) = Total\ Number\ of\ Correctly\ Classified\ Pixels\ (Diagonal) / Total\ Number\ of\ Reference\ Pixels \quad (3)$$

$$Kappa\ Coefficient\ (k) = (((TS \times TCS) - \sum(Column\ Total \times Row\ Total)) / ((TS)^2 - \sum(Column\ Total \times Row\ Total))) \times 100 \quad (4)$$

Fig. 2 **a** Photograph of YSI EcoSense pH/EC 1030 A instrument. **b**, **c** Photographs taken during the field survey

Table 1 Detail of survey site data of the Doon Valley rivers

S. No	River	Site number	Latitude	Longitude	Mean TDS (mg/L)	Mean conductivity (μS/cm)	Mean pH	Mean salinity (ppt)	Mean temperature (°C)	Mean depth (m)	Mean flow	Mean width (m)
1	*Asan*	*Asan 1*	30.28423	77.98287	516	793	7.11	0.40	16.30	1.10	Medium	2.00
2		*Asan 2*	30.28964	77.96035	512	788	7.20	0.40	18.00	0.50	Medium	4.50
3		*Asan 3*	30.29335	77.95296	505	777	7.25	0.35	18.00	1.00	Medium	5.00
4		*Asan 4*	30.29768	77.94521	394	605	7.27	0.25	18.40	0.50	Low	10.00
5		*Asan 5*	30.30639	77.93141	289	444	7.56	0.25	19.60	0.50	Low	12.50
6		*Asan 6*	30.31379	77.90797	248	381	7.49	0.15	19.60	0.75	Medium	11.00
7		*Asan 7*	30.33778	77.87174	326	502	7.27	0.25	20.30	0.75	Low	25.00
8		*Asan 8*	30.38148	77.79755	370	568	7.31	0.30	20.70	1.00	Low	30.00
9		*Asan 9*	30.42916	77.71962	336	516	7.17	0.20	21.10	1.75	Low	72.50
10		*Asan 10*	30.4348	77.66123	352	542	7.21	0.30	21.80	1.75	Low	55.00
11	*Bindal*	*Bindal 1*	30.33784	78.03925	657	1011	7.39	0.40	23.90	0.50	Low	2.50
12		*Bindal 2*	30.32573	78.03021	680	1046	7.25	0.40	24.70	0.50	Low	2.50
13		*Bindal 3*	30.32254	78.0172	684	1052	7.30	0.40	24.40	0.75	Low	4.50
14		*Bindal 4*	30.30799	78.01591	613	944	7.31	0.40	26.20	0.50	Low	6.00
15		*Bindal 5*	30.28896	78.01679	664	1021	7.27	0.40	23.90	1.00	Medium	10.00
16		*Bindal 6*	30.26079	78.02675	641	986	7.37	0.40	24.10	1.00	Medium	17.50
17	*Rispana*	*Rispana 1*	30.40962	78.09799	194	299	8.15	0.10	21.80	1.25	Medium	3.00
18		*Rispana 2*	30.38498	78.09604	215	330	8.04	0.15	22.60	0.75	Medium	2.50
19		*Rispana 3*	30.3437	78.06459	681	1048	7.41	0.40	23.50	0.75	Low	4.50
20		*Rispana 4*	30.32743	78.06188	689	1060	7.33	0.40	23.60	0.50	Low	4.00
21		*Rispana 5*	30.30397	78.06305	631	970	7.23	0.40	23.90	1.25	Medium	9.00
22		*Rispana 6*	30.28869	78.05273	617	949	7.19	0.40	24.00	0.50	Low	10.00
23		*Rispana 7*	30.25875	78.03294	642	988	7.12	0.40	25.10	1.25	Low	15.00
24	*Song*	*Song 1*	30.32052	78.15284	134	206	7.81	0.10	21.80	1.00	High	15.30
25		*Song 2*	30.33147	78.13935	141	217	7.91	0.10	21.20	1.50	High	15.50
26		*Song 3*	30.34381	78.1332	218	335	8.23	0.15	22.60	0.50	Medium	7.50
27		*Song 4*	30.29473	78.11942	245	377	7.90	0.20	26.00	1.00	Medium	40.00
28		*Song 5*	30.24466	78.13934	259	399	7.66	0.20	27.00	1.00	Medium	26.00
29		*Song 6*	30.19062	78.13571	278	428	8.00	0.20	22.50	0.50	Medium	29.00
30		*Song 7*	30.07232	78.17928	493	759	7.21	0.30	22.60	1.00	Medium	65.00
31		*Song 8*	30.04391	78.23835	551	847	7.48	0.35	21.90	1.50	Medium	57.00
32	*Suswa*	*Suswa 1*	30.25046	78.02675	667	1026	6.99	0.40	24.20	1.50	Medium	25.00
33		*Suswa 2*	30.23941	78.0246	657	1010	7.26	0.40	24.80	1.25	Low	17.50
34		*Suswa 3*	30.22593	78.03283	633	974	7.13	0.40	25.00	1.50	Medium	17.50
35		*Suswa 4*	30.18147	78.07273	630	969	7.26	0.40	26.20	1.00	Low	10.00
36		*Suswa 5*	30.16009	78.09635	633	973	7.49	0.40	25.70	1.50	Medium	17.50

Table 2 Rating criteria of kappa coefficient

S. No	Kappa coefficient	Strength of agreement
1	< 0	Poor
2	0.00–20.00	Slight
3	21.00–40.00	Fair
4	41.00–60.00	Moderate
5	61.00–80.00	Substantial
6	81.00–100	Almost perfect

Rupke and Sharma's (1974) map of the Western Kumaon Himalaya was georeferenced through ArcGIS desktop software for geology data, and the soil type data was downloaded from the Bhoomi portals of the National Bureau of Soil Survey and Land Use Planning (ICAR-NBSS and LUP 2024).

Multi-criteria decision-making analysis using AHP techniques

Multi-criteria decision-making analysis using the analytical hierarchical process (AHP) is a widely recognized and effective method for assessing RRZ. This method integrates various thematic layers to provide a comprehensive analysis. For this study, 15 different thematic layers were considered, including factors influencing river risk occurrence and weighted according to their relative impact and expert opinion. A higher weight indicates a layer with a more significant impact on river risk, while a lower weight suggests lesser significance (Arulbalaji et al. 2019). Weights for each parameter were assigned based on Saaty's scale of relative importance (ranging from 1 to 9), where a value of 9 indicates extreme importance, 8 extreme to very strong importance, 7 very strong importance, 6 strong plus importance, 5 strong importance, 4 moderate plus importance, 3 moderate importance, 2 weak importance, and 1 equal importance (Saaty 1980). This scale helps quantify the relative influence of each parameter on river risk, with higher values indicating a stronger influence. The assignment of weights also considered past studies and field experience, ensuring a robust and informed analysis (Topuz and Deniz 2023). Following the classification of weights, all thematic layers were compared in a pair-wise comparison matrix (Table 3) to assess their relative importance. Subsequently, the subclasses of each thematic layer were reclassified using the reclassify tool in ArcGIS Desktop software 10.6.1, with ranks assigned on a scale from 0 to 9 according to their influence on river risk. Table 4 presents the assigned ranks and corresponding weights for each thematic layer.

To ensure consistency in the weight assignment process, the consistency ratio (CR) was calculated (Eq. 6). The steps for this calculation included computing the principal eigenvalue (λ_{max}) and calculating the consistency index (CI) using the equation (Eq. 5):

$$\mathrm{CI} = \left(\lambda_{max} - n\right)/(n - 1) \tag{5}$$

where λ_{max} is the principal eigenvalue and n is the number of comparisons.

Ideally, for a perfectly consistent matrix, λ_{max} should equal n. However, due to human judgment, some inconsistency is usually present, making λ_{max} slightly greater than n. This method ensures that the weights assigned are reliable and reflect a consistent judgment across all thematic layers.

$$\begin{gathered}\mathrm{CI} = (15.692 - 15)/(15 - 1) = 0.0494 \\ \mathrm{CR} = \mathrm{CI}/\mathrm{RCI}\end{gathered} \tag{6}$$

where RCI is random consistency index value, whose values were obtained from Saaty's standard (Table 5).

$$\mathrm{CR} = 0.0494/1.59 = 0.0311$$

According to Saaty (1990), a consistency ratio (CR) of 0.10 or less is acceptable for continuing the analysis, as it indicates that the judgments made are reasonably consistent. If the CR exceeds 0.10, it suggests inconsistency in the judgment matrix, necessitating a revision to identify and correct the inconsistencies. In our analysis, the threshold CR value calculated is 0.0311, well below the 0.10 limit. This indicates that the judgments used in the weight assignment process are consistent, validating the reliability of our results and allowing us to proceed with the analysis confidently.

To generate the RRZ map of the Doon Valley rivers, all 15 thematic layers were integrated with the weighted overlay analysis method in the GIS platform using equation (Eq. 7)

$$\mathrm{RRZ} = \sum \left(X_A \times Y_B\right) \tag{7}$$

where RRZ is river risk zone; X represents the weight of the thematic layers; Y represents rank of the thematic layers' subclass; $A = (1, 2, 3, \ldots\ldots, X)$ represents the thematic layers; and $B = (1, 2, 3, \ldots\ldots, Y)$ represents the thematic layer classes.

The final RRZ map was classified into very high, high, medium, low, and very low zones. Figure 3 illustrates the flow chart of the methodology adopted in this study.

Table 3 Pair-wise comparison matrix table of 15 thematic layers chosen for the present study

Parameter	Assigned weight	TDS	Conductivity	pH	Salinity	Temperature	Depth	Drainage density	LULC	Slope	Elevation	Flow	Width	Soil type	Geology	Aspect	Geometric mean	Normalized weight
TDS	9	**1.00**	1.00	1.125	1.125	1.286	1.286	1.286	1.286	1.50	1.50	1.80	1.80	2.25	2.25	3.00	1.487	0.095
Conductivity	9	1.00	**1.00**	1.125	1.125	1.286	1.286	1.286	1.286	1.50	1.50	1.80	1.80	2.25	2.25	3.00	1.487	0.095
pH	8	0.889	0.889	**1.00**	1.00	1.143	1.143	1.143	1.143	1.333	1.333	1.60	1.60	2.00	2.00	2.667	1.321	0.084
Salinity	8	0.889	0.889	1.00	**1.00**	1.143	1.143	1.143	1.143	1.333	1.333	1.60	1.60	2.00	2.00	2.667	1.321	0.084
Temperature	7	0.778	0.778	0.875	0.875	**1.00**	1.00	1.00	1.00	1.167	1.167	1.40	1.40	1.75	1.75	2.333	1.156	0.074
Depth	7	0.778	0.778	0.875	0.875	1.00	**1.00**	1.00	1.00	1.167	1.167	1.40	1.40	1.75	1.75	2.333	1.156	0.074
Drainage density	7	0.778	0.778	0.875	0.875	1.00	1.00	**1.00**	1.00	1.167	1.167	1.40	1.40	1.75	1.75	2.333	1.156	0.074
LULC	7	0.778	0.778	0.875	0.875	1.00	1.00	1.00	**1.00**	1.167	1.167	1.40	1.40	1.75	1.75	2.333	1.156	0.074
Slope	6	0.667	0.667	0.75	0.75	0.857	0.857	0.857	0.857	**1.00**	1.00	1.20	1.20	1.50	1.50	2.00	0.991	0.063
Elevation	6	0.667	0.667	0.75	0.75	0.857	0.857	0.857	0.857	1.00	**1.00**	1.20	1.20	1.50	1.50	2.00	0.991	0.063
Flow	5	0.556	0.556	0.625	0.625	0.714	0.714	0.714	0.714	0.833	0.833	**1.00**	1.00	1.25	1.25	1.667	0.826	0.053
Width	5	0.556	0.556	0.625	0.625	0.714	0.714	0.714	0.714	0.833	0.833	1.00	**1.00**	1.25	1.25	1.667	0.826	0.053
Soil type	4	0.444	0.444	0.50	0.50	0.571	0.571	0.571	0.571	0.667	0.667	0.80	0.80	**1.00**	1.00	1.333	0.661	0.042
Geology	4	0.444	0.444	0.50	0.50	0.571	0.571	0.571	0.571	0.667	0.667	0.80	0.80	1.00	**1.00**	1.333	0.661	0.042
Aspect	3	0.333	0.333	0.375	0.375	0.429	0.429	0.429	0.429	0.50	0.50	0.60	0.60	0.75	0.75	**1.00**	0.496	0.032

Table 4 Assigned weightage and rank to each thematic layer for RRZ

Layer	Weightage	Classes	Rank
Total dissolved solids (TDS)	9	≤ 200 mg/L	1
		201–350 mg/L	3
		351–500 mg/L	5
		501–650 mg/L	7
		651–689 mg/L	9
Conductivity	9	≤ 300 µS/cm	1
		301–500 µS/cm	3
		501–750 µS/cm	5
		751–1000 µS/cm	7
		1001–1060 µS/cm	9
pH	8	≤ 7.20	8
		7.21–7.70	5
		7.71–8.23	2
Salinity	8	≤ 0.20 ppt	3
		0.21–0.30 ppt	6
		> 0.31–0.40 ppt	9
Temperature	7	≤ 20°	2
		21–25°	5
		> 25°	8
Depth	7	≤ 0.8 m	2
		0.81–1.30 m	5
		> 1.30 m	8
Drainage density	7	≤ 5 km/km^2	1
		5.1–6.5 km/km^2	3
		6.6–8 km/km^2	5
		8.1–9.5 km/km^2	7
		9.6–10.6 km/km^2	9
LULC	7	Built-up	7
		Agricultural land	6
		Forest area	2
		Wasteland	5
		Dry riverbed	4
		Waterbodies	9
Slope	6	≤ 2°	9
		3–5°	7
		6–10°	5
		11–20°	3
		21–63°	1
Elevation	6	≤ 500 m	9
		501–700 m	7
		701–900 m	5
		901–1200 m	3
		1201–1919 m	1
Flow	5	Low	8
		Medium	5
		High	2
Width	5	≤ 10 m	2
		11–20 m	5
		> 20 m	8

Table 4 (continued)

Layer	Weightage	Classes	Rank
Soil type	4	Sandy-skeletal	8
		Loamy-skeletal	6
		Coarse-loamy	4
		Fine-loamy	7
		Clayey	2
		Waterbodies	8
Geology	4	Alluvium	8
		Chandpur	5
		Lower tal	1
		Upper tal	1
		Krol sandstone + krol A	2
		Low grade	1
		Blaini/Infra Krol	2
		Nagthat/Shimla	2
		Damta	4
Aspect	3	Flat (− 1)	1
		North (0–22.5°) (337.5–360°)	2
		Northeast (22.5–67.5°)	3
		East (67.5–112.5°)	6
		Southeast (112.5–157.5°)	7
		South (157.5–202.5°)	8
		Southwest (202.5–247.5°)	6
		West (247.5–292.5°)	7
		Northwest (292.5–337.5°)	5

Results

Total dissolved solids (TDS)

The findings reveal that the Bindal, Rispana, and Suswa rivers generally have TDS values exceeding 500 mg/L (Fig. 4), which is over the permissible limits by Bureau of Indian Standard (BIS), American Public Health Association (AHPA), and World Health Organization (WHO). Near the source, the Asan River exhibits TDS levels above 500 mg/L, primarily due to the presence of municipal solid waste and sewage drains. The TDS values of the Song River also increase significantly near the Song and Suswa Rivers confluence until it merges with the Ganga River. The observed variations in TDS levels reflect the influence of anthropogenic activities, such as the expansion of urban areas and agricultural land use (Suthar et al. 2010). High TDS values across the Doon Valley rivers suggest significant water quality degradation, necessitating targeted management strategies to mitigate pollution sources. These TDS results underscore the urgent need for more effective water quality management practices, including improved sewage treatment and sustainable agricultural methods to mitigate impacts on the river ecosystem (Liu et al. 2021).

Conductivity

The conductivity values in this study ranged from 206 to 1060 µS/cm (Fig. 5), highlighting the impact of various land uses on water quality. The findings indicate that the Bindal,

Table 5 Saaty's random consistency index value for different values of *n*

The consistency indices of randomly generated reciprocal matrices															
Order of the matrix															
N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RCI value	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

Rispana, and Suswa rivers predominantly have conductivity values exceeding 500 µS/cm, which is the permissible limit set by APHA for aquatic life. Similarly, the Song River also exhibits conductivity levels above 500 µS/cm near Doiwala until it joins the Ganga River near Tehari Farm. For the Asan River, conductivity values exceed 500 µS/cm near its source and downstream from the Sheeshamabada solid waste disposal site until its confluence with the Yamuna River. However, near the Himalayan Environmental Studies and Conservation Organization (HESCO), conductivity values

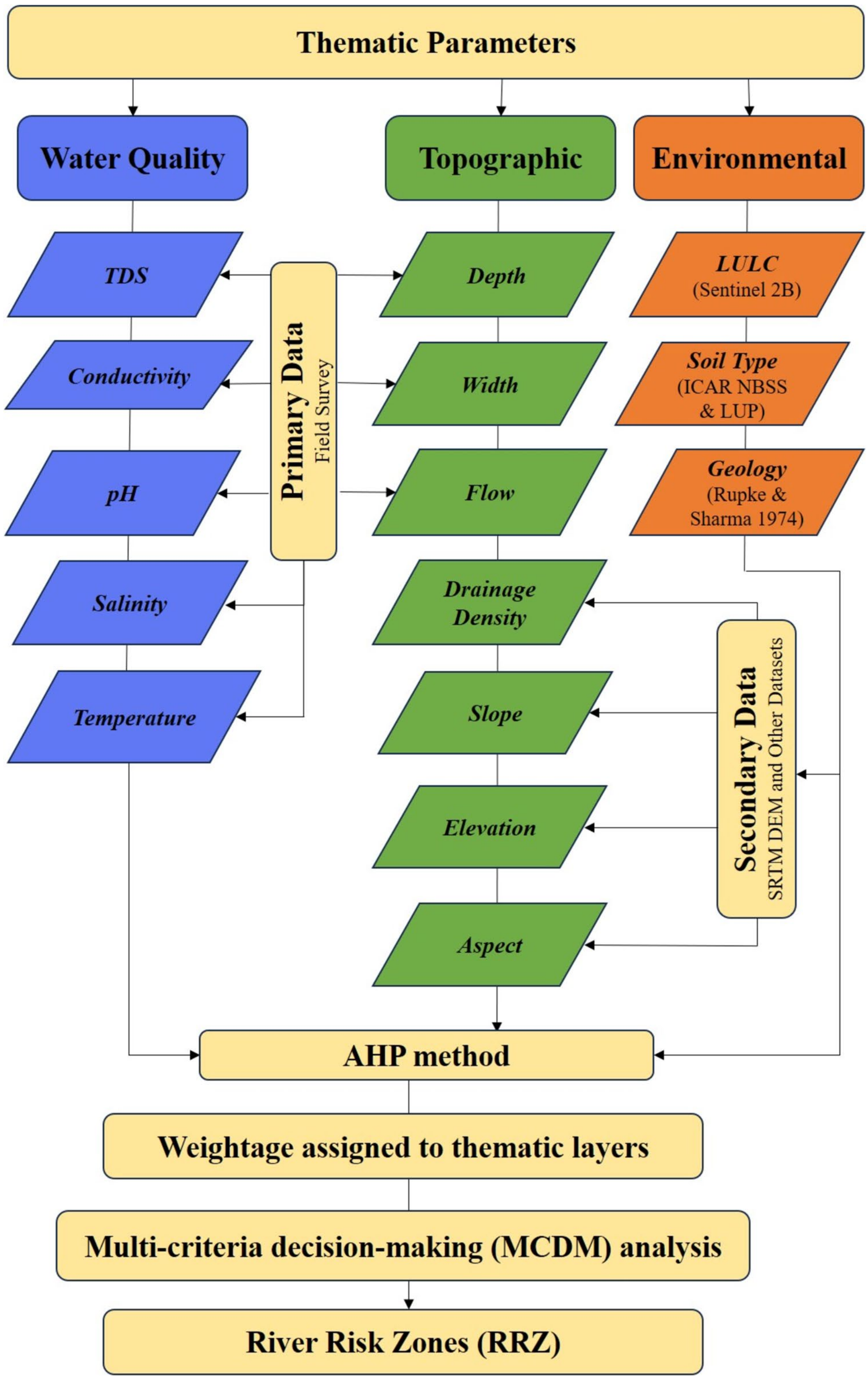


Fig. 3 Flow chart of the methodology

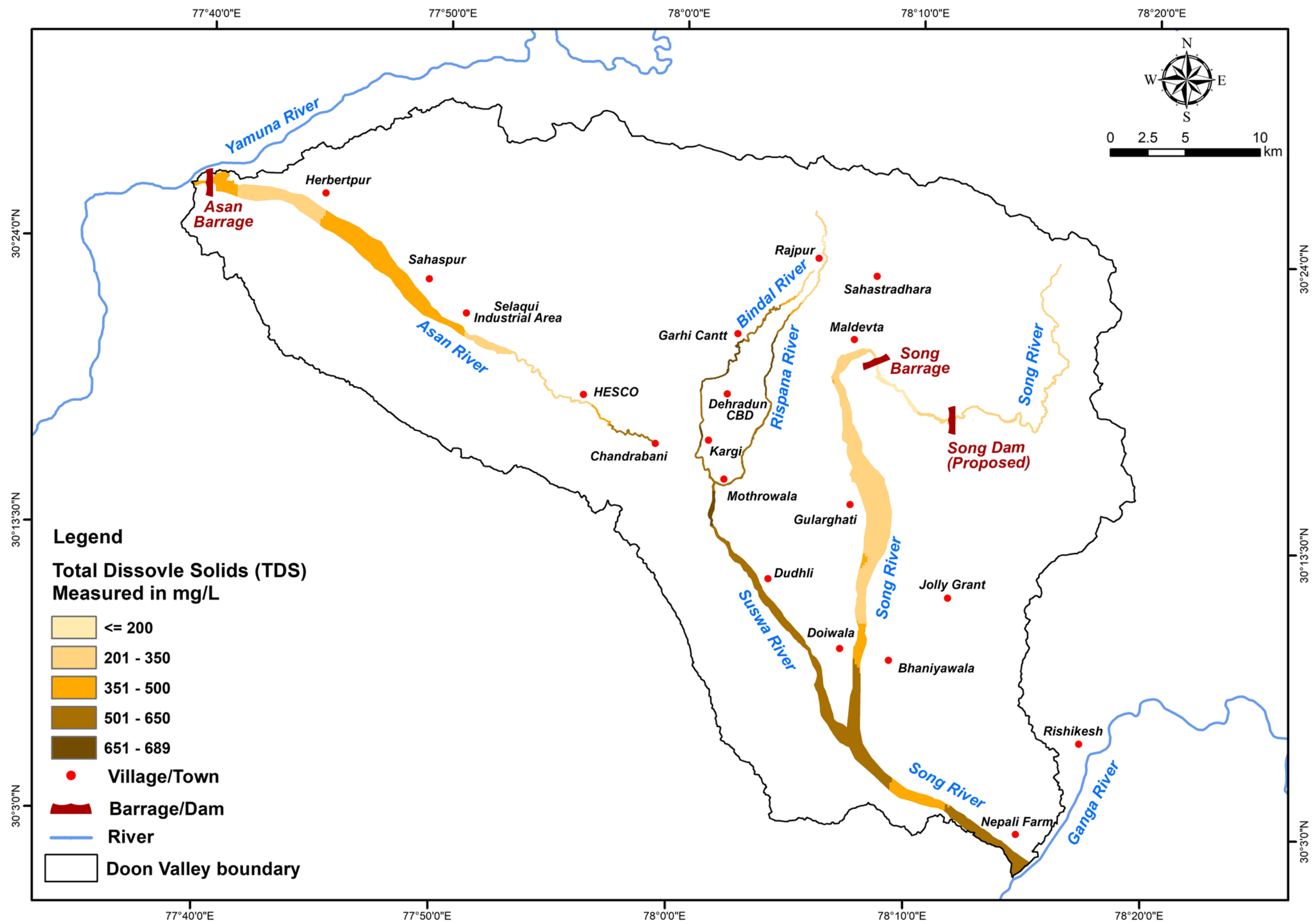


Fig. 4 TDS map of the Doon Valley rivers

drop below 500 µS/cm due to their nature-based conservation efforts in the Asan Riverscape. Higher conductivity levels were associated with river stretches experiencing significant municipal sewage discharge and extensive agricultural activity (Kumar and Mathur 1989). In contrast, areas with minimal human interference showed lower conductivity, indicating relatively unaltered water quality. Increased conductivity also affects aquatic life, which is often sensitive to changes in ion concentrations (Purohit and Singh 2020). The overall high conductivity values of the Doon Valley rivers suggest the need for targeted management strategies to reduce pollution.

pH

The study found no significant variation in pH levels across the Doon Valley rivers. This consistency suggests a stable water quality over time, which is crucial for evaluating the long-term health and resilience of the aquatic ecosystems in the region. The overall pH levels in these rivers fall within the regulatory range of 6.5–8.5, which is considered suitable for aquatic life, as per the guidelines of BIS, APHA, and WHO (Fig. 6), which is suitable for supporting healthy aquatic ecosystems (Somridhivej and Boyd 2017). A slightly alkaline pH has been observed near the lower stretches of the rivers. The differences in pH values among the rivers may be attributed to geological variations, land use practices like agriculture and urbanization, and natural processes (Mosley et al. 2014). Ongoing monitoring and management are vital to address potential pollution threats and to maintain the sustainability of these critical river systems for both ecological balance and human needs.

Salinity

The overall salinity value in the Doon Valley rivers is within the permissible limit of 0.5 parts per thousand (ppt) for freshwater as per BIS, APHA, and WHO (Fig. 7). Increased

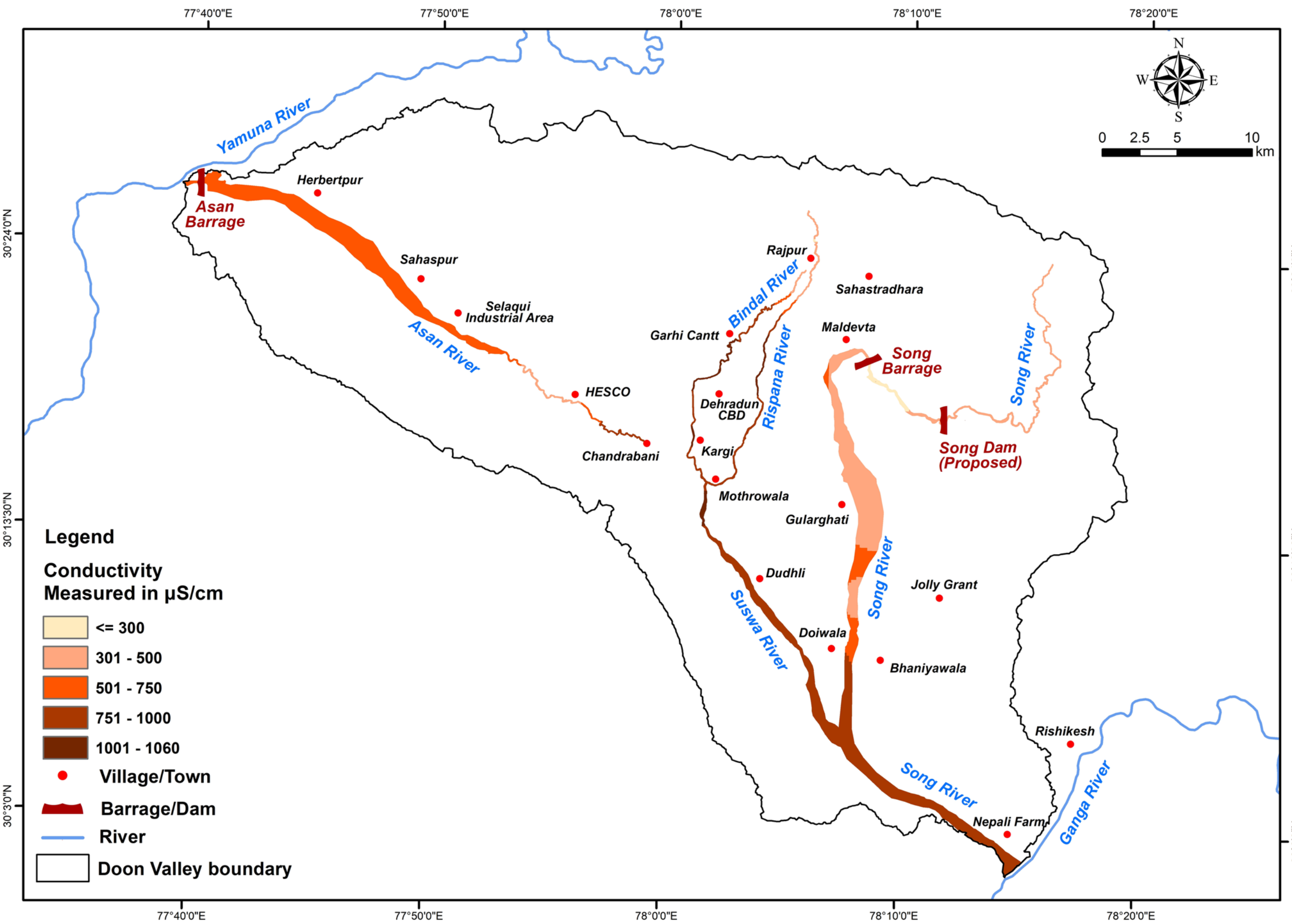


Fig. 5 Conductivity map of the Doon Valley rivers

salinity levels were notably observed in regions with intensive agricultural practices and insufficient sewage treatment, highlighting the substantial influence of human activities. There is a clear relationship between salinity, total dissolved solids (TDS), and conductivity, as higher salt concentrations contribute to increased TDS and conductivity levels. Increased salinity can adversely affect aquatic life and degrade drinking water quality. These findings underline the critical need for enhanced salinity management strategies to maintain river systems' ecological integrity and functionality. Recommended measures include better waste management, controlled agricultural practices, and the restoration of riparian buffer zones to mitigate the impacts of salinity on these freshwater resources (Cañedo-Argüelles et al. 2013).

Temperature

River temperature is critical in assessing river health and the risks associated with aquatic ecosystems. Temperature influences aquatic organisms' metabolic rates, oxygen solubility, and water's chemical composition. In this study, the overall water temperature is between 16 and 27 °C (Fig. 8). Water temperature can affect aquatic organisms' metabolic rates and biological activity. In the Doon Valley, the temperature of water should be between 13 and 28 °C to flourish aquatic life (Rana et al. 2021). The high river temperatures, often caused by reduced flow, sewage effluent, agricultural runoff, and climate change, can lead to thermal stress on aquatic life, disrupting ecosystems and reducing biodiversity (Yadav et al. 2015). Monitoring river temperature is essential for identifying potential risks, such as spreading invasive species or declining sensitive native species, and implementing effective management strategies to protect and sustain river ecosystems.

Depth

The depth of the Doon Valley rivers is categorized into three distinct classes: ≤ 0.8 m, 0.81–1.30 m, and > 1.30 m (Fig. 9). These classifications help in understanding the distribution

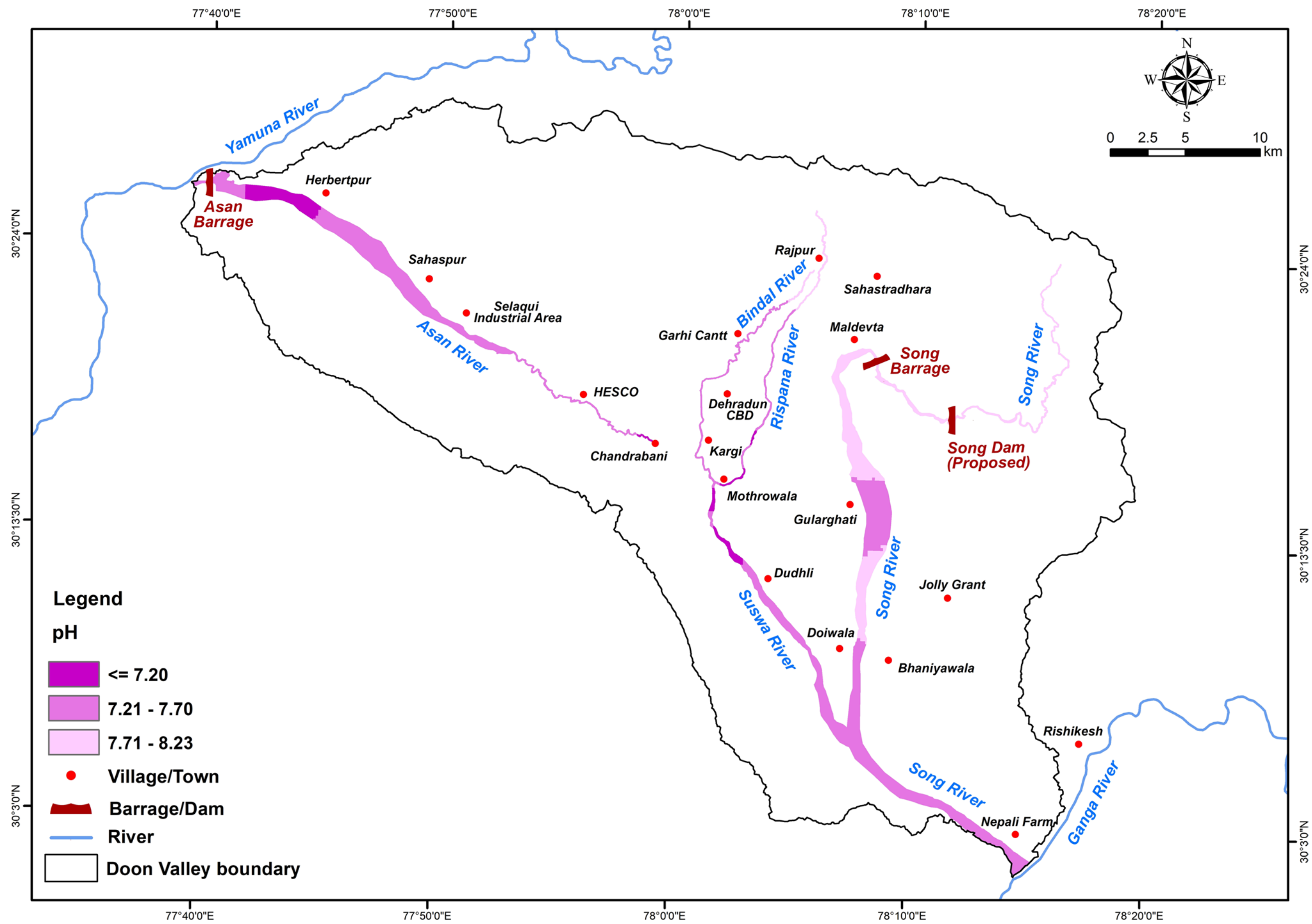


Fig. 6 pH map of the Doon Valley rivers

of shallow and deep sections across the rivers, which is crucial for assessing flood risks, aquatic habitats, and sediment transport within the valley. The overall depth in the Doon Valley rivers is very shallow. It revealed significant variability, with shallower segments primarily in areas of steep slope, high sediment deposition and higher human modifications. Deeper segments are in regions with gentle slopes, low sediment deposition, and lesser human modifications (Brookes 1994). These variations affect river flow capacity, flood risks, and aquatic habitats. Effectively managing these depth disparities is essential for maintaining ecological balance and mitigating flood risks.

Drainage density

Drainage density is defined as the total length of streams per unit area, reflecting how closely packed the river channels are within a particular region. According to Mani and Kumar (2020), flatter surfaces tend to have higher drainage density and vice versa. As shown in Fig. 10, drainage density in the study area is categorized into five classes: very low (≤ 5 km/km^2), low (5.1–6.5 km/km^2), medium (6.6–8 km/km^2), high (8.1–9.5 km/km^2), and very high (9.6–10.6 km/km^2). Most of the area falls into the medium, high, and very high drainage density categories. Drainage density indicates landscape subdivision and the potential for runoff in a catchment area (Singh et al. 2014). In regions with high drainage density on flatter surfaces, infiltration rates are elevated, leading to reduced runoff as water percolates into the soil and reaches groundwater. However, if urban effluents and sewage drains contaminate this infiltrating water, it poses significant risks to human and biotic health (Tedoldi et al. 2016). Contaminated groundwater can spread waterborne diseases and adversely affect aquatic ecosystems and biodiversity (Bashir et al. 2020).

Land use/land cover (LULC)

LULC reflects human utilisation of land resources, particularly in agriculture and urban development (Lambin

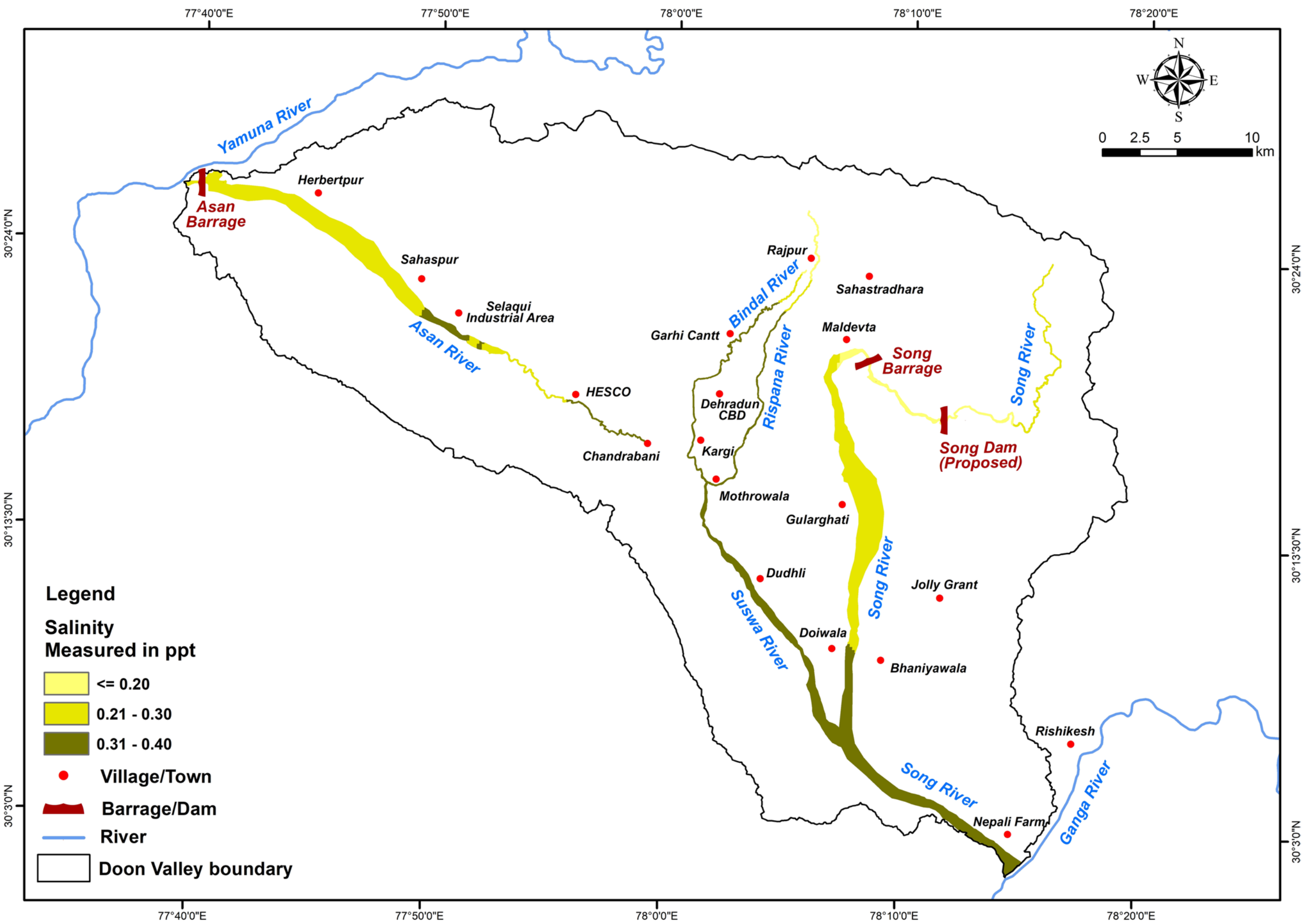


Fig. 7 Salinity map of the Doon Valley rivers

et al. 2003). Water resources face continuous pressure due to land use practices and climate change (Kløve et al. 2014; Mani et al. 2023a, b, c). The LULC classification enables the prediction of diverse physical processes occurring on Earth's surface. Six LULC classes were identified: built-up, agricultural land, forest, wasteland, dry riverbed, and waterbodies, as shown in Fig. 11. Notably, forest cover dominates the landscape, covering 35.67% of the area, followed by dry riverbed area at 23.01% and agriculture land area at 18.28%. Wasteland constitutes 9.91% of the area, while waterbodies and built-up occupy 8.33% and 4.80% respectively (Table 6). The classification achieved an overall accuracy of 0.79 and a kappa coefficient of 73%, indicating a substantial as per kappa criteria (Table 7). The anthropogenic impact in Doon Valley significantly affects the biodiversity and health of the Asan, Bindal, Rispana, Song, and Suswa rivers (Mani et al. 2023a, b, c). Doon Valley's climate and rising tourism pressure further contribute to urban expansion (Dey et al. 2018). This increasing urban footprint and other human activities threaten river health and biodiversity (Rana et al. 2017). Analysing LULC patterns in the riverscape offers crucial insights into how human activities and natural resources interact, reshaping the landscape (Garg et al. 2019). This research enhances our understanding of land–water dynamics, guiding conservation efforts and sustainable land management practices to protect river ecosystems.

Slope

The slope represents the steepness of the terrain. For this study, the slopes in the Doon Valley are classified into five categories: very gentle (≤2°), gentle (3 to 5°), moderate (6 to 10°), steep (11 to 20°), and very steep (21 to 63°). As per Fig. 12, most of the area has a very gentle slope. The areas with very gentle slopes experience minimal runoff, making them particularly suitable for groundwater infiltration (Mani et al. 2023a, b, c).

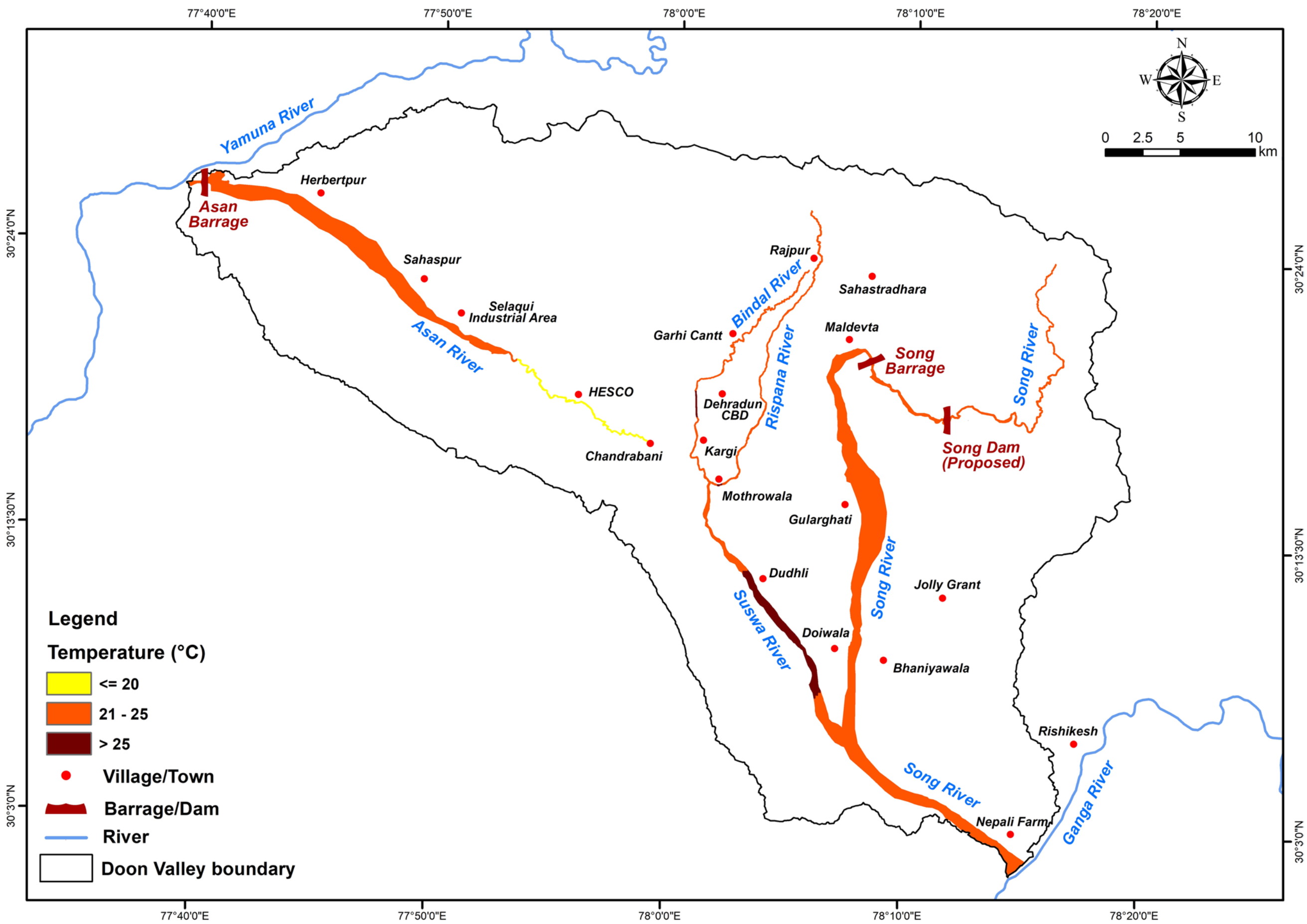


Fig. 8 Temperature map of the Doon Valley rivers

Elevation

In Fig. 13, the Doon Valley is divided into five elevation classes: very low (≤ 500 m), low (501–700 m), moderate (701–900 m), high (901–1200 m), and very high (1201–1919 m). Most of the region falls within the low to very low elevation range, suggesting an indirect relationship between elevation, slope, and drainage density. Lower elevations tend to correspond with flatter slopes, which, in turn, are associated with higher drainage density (Mani et al. 2022).

Flow

River flow, or streamflow, can be categorized into two types: discharge, which refers to the volume of water moving through a river channel over a specific period, typically measured in cubic meters per second (m^3/s), and velocity, which refers to the speed at which water moves through a river channel, typically measured in meters per second (m/s). For this study, we have focused on river flow as velocity and used the float method to analyse it. This method involves tracking the time it takes for a floating object to travel a known distance along the river. Flow is a critical parameter in determining the ecosystem functioning, river's health, and its ability to support aquatic life. The flow is classified into three categories: low (< 0.5 m/s), medium (0.5–2 m/s) and high (> 2 m/s). Most of the area exhibits low-to-medium flow (Fig. 14), indicating a high drainage density combined with significant infiltration and reduced runoff. It suggests that much of the water percolates into the ground, replenishing groundwater supplies rather than contributing to surface runoff. Consequently, this can mitigate the risk of flooding but also highlights the importance of maintaining water quality, as contaminants from urban and agricultural activities can infiltrate the soil and potentially affect groundwater resources (Tedoldi et al. 2016). Understanding and monitoring river flow is essential for effective water resource management, flood control, and ensuring the sustainability of riverine ecosystems.

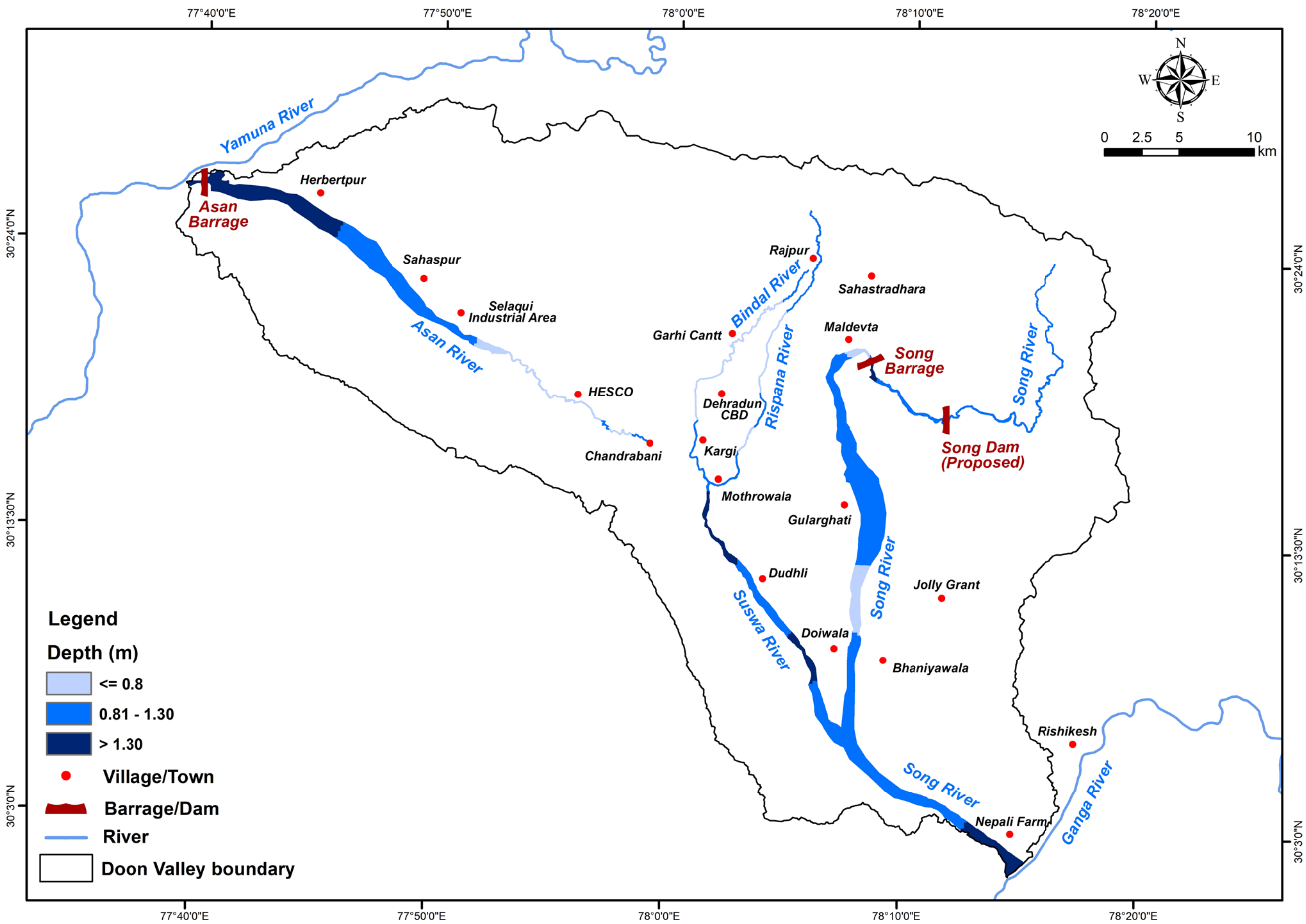


Fig. 9 Depth map of the Doon Valley rivers

Width

For RRZ assessment, width is another crucial parameter for evaluating potential flooding and erosion impacts. A wider river can accommodate more water but may also increase the risk of floodplain inundation during monsoon season. Narrower rivers have higher flood risks due to limited capacity and higher runoff in the valley region (Dwivedi et al. 2024). In this research, the channel width of the Asan, Song, and Suswa rivers is over 20 m in the maximum stretches (Fig. 15). In the Bindal and Rispana rivers, the channel width is under 10 m due to the presence of urbanization in both banks of the rivers. The narrow width restricts water flow, increasing the likelihood of overflow and flooding, especially during the rainy season. Additionally, ongoing urban effluent and sewage discharge further complicate the situation by contaminating the water and reducing the river's capacity (Mani et al. 2024). Assessing river width helps predict flood extent, design effective mitigation measures, ensure appropriate land use planning and enhance sewage treatment infrastructure (Dwivedi et al. 2024). Accurate width measurements, flow data, and topography provide a comprehensive risk profile for effective management and safety planning.

Soil type

Soil type is an essential parameter for RRZ assessment. The soil type was classified into six classes (Fig. 16): sandy-skeletal, loamy-skeletal, coarse-loamy, fine-loamy, clayey, and waterbodies (ICAR-NBSS & LUP 2024). The majority of the area has loamy-skeletal soil types followed by fine-loamy (Mani et al. 2024). Fine loamy and sandy-skeletal soils exhibit more excellent water infiltration permeability than clayey soils, primarily due to alluvium as the parent material. This characteristic allows for more efficient water movement through the soil profile, enhancing groundwater recharge in areas where these soil types are prevalent.

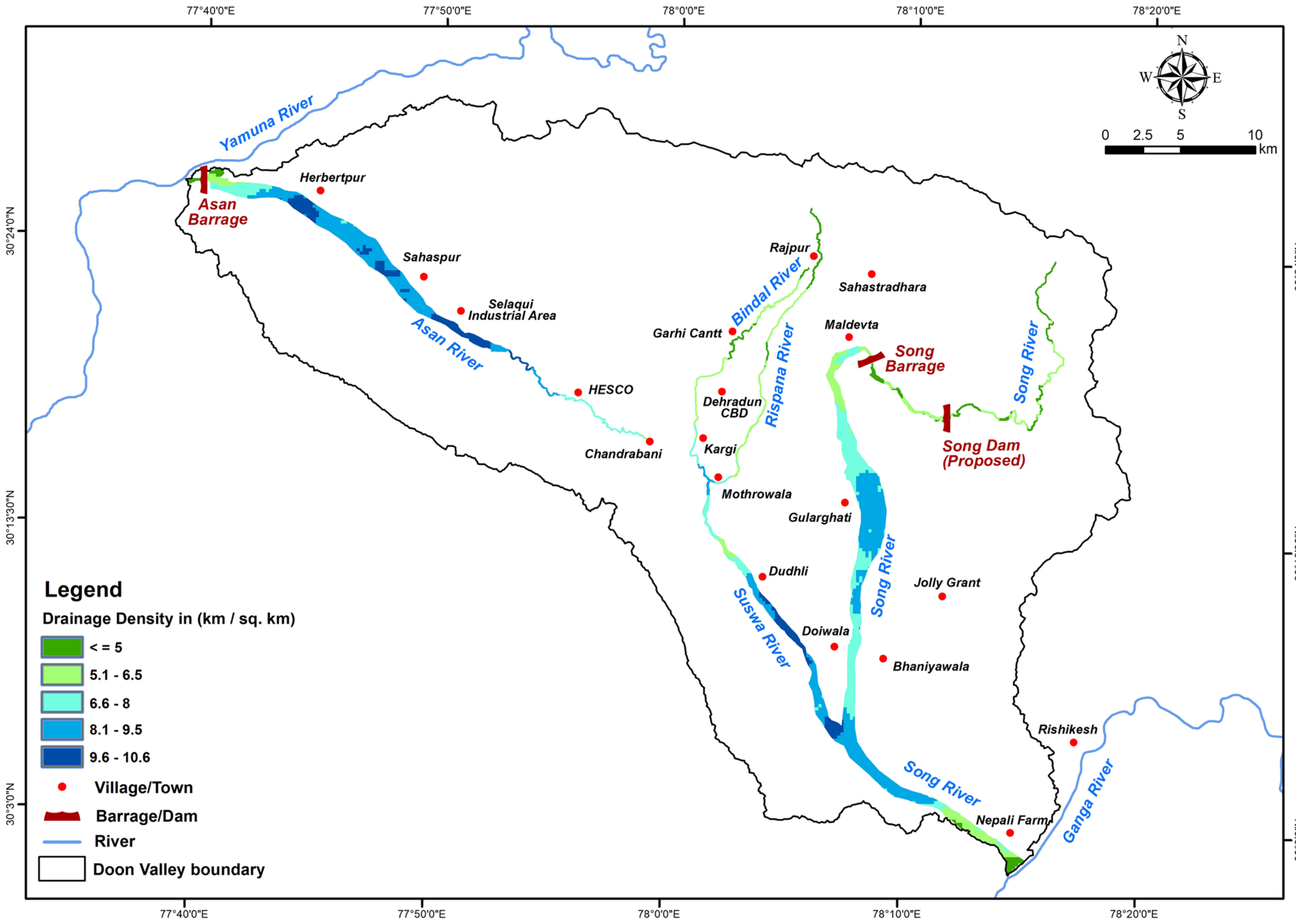


Fig. 10 Drainage density map of the Doon Valley rivers

Geology

Geology is another critical parameter for RRZ mapping, as it provides information on geology formations and their infiltration rates. The nine classes of geology formation are shown in Fig. 17: Alluvium, Blaini/Infra Krol, Chandpur, Damta, Krol Sandstone + Krol A, Low Grade, Lower Tal, Nagthat, and Upper Tal (Rupke and Sharma 1974). The alluvium is present mainly in the area, followed by Damta (Mani et al. 2024). The alluvium formation is more susceptible to river risk due to high permeability and high infiltration, whereas Krol, nagthat, blaini, damta, and Chandpur formations are more prone to landslides (Rupke and Sharma 1974; Mandal et al. 2024).

Aspect

The aspect defines the slope's direction (Mani et al. 2022). The aspect is classified as (0–22.5°) is north, (22.5–67.5°) is northeast, (67.5–112.5°) is east, (112.5–157.5°) is southeast, (157.5–202.5°) is south, (202.5–247.5°) is southwest, (247.5–292.5°) is west, (292.5–337.5°) is northwest, and (337.5–360°) is again north. For this study, the direction of the slope is on two sides, one west-facing and another southwest-south facing as shown in Fig. 18. In comparison to the east-facing slope, the west and south-facing slope has more vegetation cover and more moisture (Mani et al. 2024).

River risk zone (RRZ) assessment

In the Doon Valley rivers, several parameters were analysed, including TDS, conductivity, pH, salinity, temperature, depth, drainage density, land use/land cover (LULC), elevation, slope, flow, width, soil type, geology, and aspect to identify the RRZ. The results from the AHP method indicated CI and CR values of 0.0494 and 0.0311, respectively, with the CR value being acceptable as it is below the 0.10 threshold, allowing for confident continuation of the analysis. Following

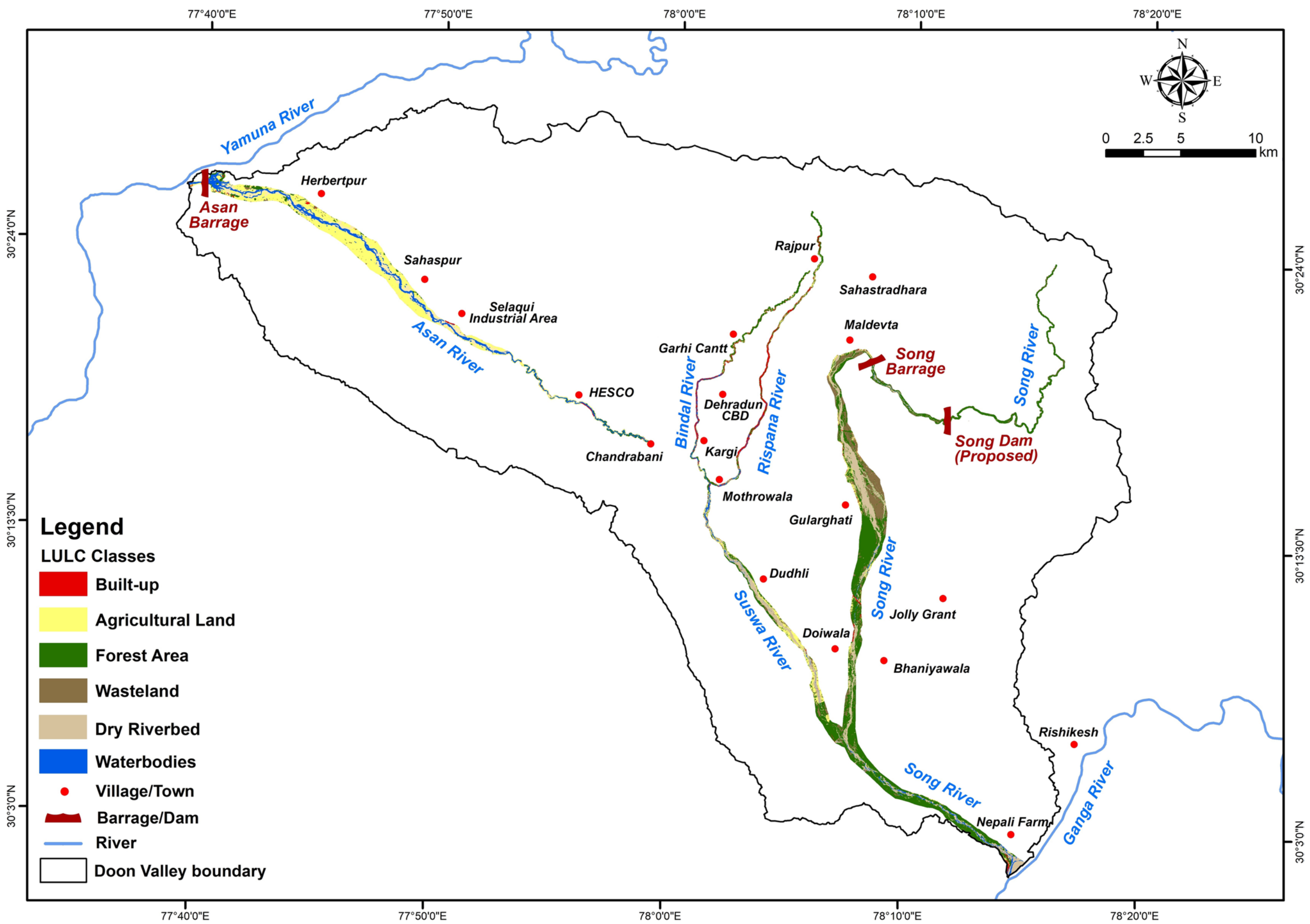


Fig. 11 LULC map of the Doon Valley rivers

Table 6 Table for LULC area statistics

S. No	LULC classes	Area in km^2	Area in %
1	Built-up	3.87	4.80
2	Agriculture land	14.74	18.28
3	Forest area	28.76	35.67
4	Wasteland	7.99	9.91
5	Dry riverbed	18.55	23.01
6	Waterbodies	6.72	8.33
Total area		80.63	100

this, the weighted overlay method was applied to generate the RRZ in the Doon Valley. The resulting RRZ map is divided into very high, high, medium, low, and very low-risk zones (Fig. 19), and the aerial spread percentage of these categories is 12.45%, 43.93%, 33.71%, 2.93%, and 6.98%, respectively (Table 8). The risk zone assessment reveals that the Bindal, Rispana, and Suswa rivers and the upper stretch of the Asan River are the most susceptible, with very high and high-risk zones occurring predominantly along their courses. It suggests these rivers face significant environmental pressures, likely due to urbanisation, municipal solid waste, sewage effluent, and agriculture expansion and runoff (Mani et al. 2022). The Asan River demonstrates a high to medium risk zone, indicating some vulnerability but less than the previously mentioned rivers. Meanwhile, the Song River has medium, low, and very low-risk zones, primarily along its upper and middle stretches, suggesting lower exposure to threats, especially human disturbance. However, the Song River exhibits a high and very high-risk zone near its confluence with the Suswa River and extending up to its junction with the Ganga River (Nayal and Suthar 2022).

Discussion

RRZ assessment using advanced GIS and AHP methods is crucial as it helps better understand and manage threats to the fluvial ecosystems, human settlements,

Table 7 Accuracy assessment table

	LULC class	Reference data							User accuracy
		Built-up	Agri-cultural land	Forest area	Wasteland	Dry riverbed	Waterbodies	Total (user)	
Classified data	Built-up	2	0	0	1	0	0	3	0.67
	Agricultural land	2	18	2	0	0	0	22	0.82
	Forest Area	1	5	25	0	0	0	31	0.81
	Wasteland	2	2	0	5	1	0	10	0.50
	Dry Riverbed	0	0	0	2	12	0	14	0.86
	Waterbodies	0	0	0	0	1	9	10	0.90
	Total (Producer)	7	25	27	8	14	9	90	
	Producer Accuracy	0.29	0.72	0.93	0.63	0.86	1.00		
	Overall accuracy (OA) = 0.79								
	Kappa coefficient (k) = 73%								

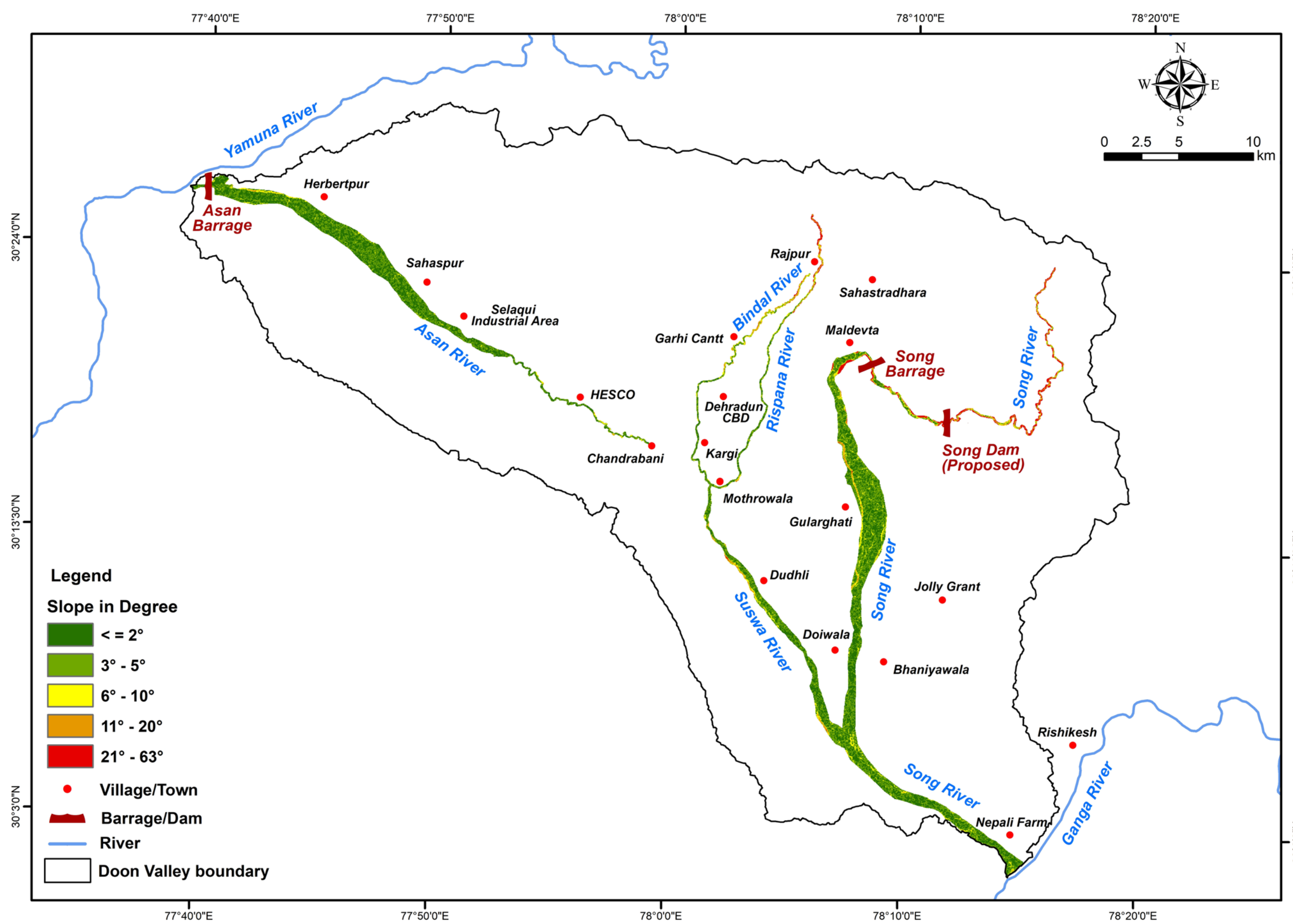


Fig. 12 Slope map of the Doon Valley rivers

and biodiversity. In the Doon Valley, there is an array of stressors on river system advances, such as rapid urbanisation, deforestation, and agriculture expansion, making it imperative to identify the risk zones for sustainable management of rivers (Rana et al. 2021; Mani et al. 2022, 2023a, b, c). Changes in water quality parameters

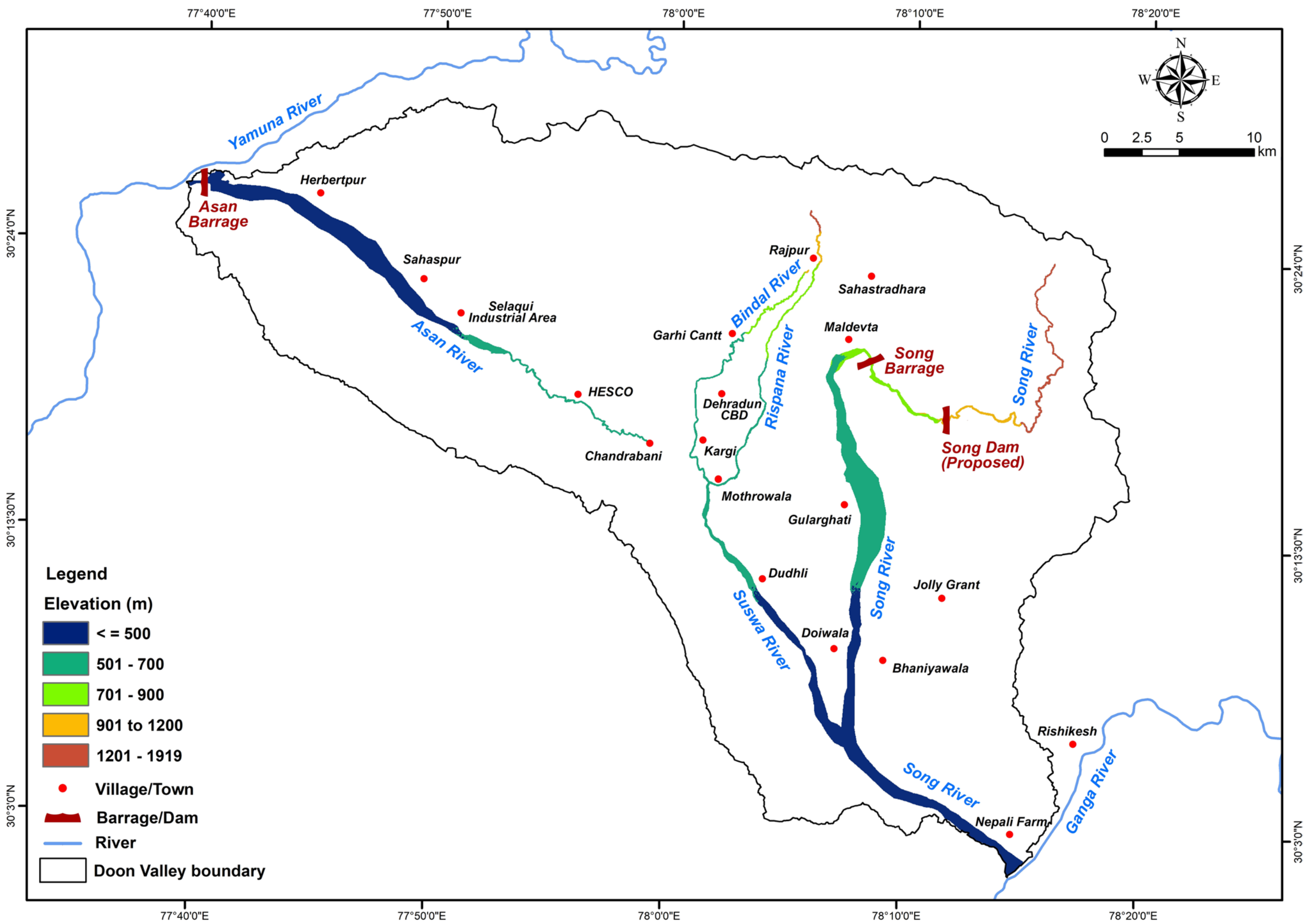


Fig. 13 Elevation map of the Doon Valley rivers

like TDS, conductivity, pH, and salinity because of municipal waste discharge, agricultural runoff, and industrial discharge contribute towards higher risks to these water bodies by an increased degradation phase (Mishra et al. 2022). Another important parameter, temperature, is one of the principal consequences of river risk and directly affects aquatic biodiversity. Warmer temperatures, arising from urban runoff and deforestation, lower the dissolved oxygen levels in the water, making it difficult for aquatic life to adapt (Yadav et al. 2015). Topography parameters and environmental factors influence river risk by affecting water flow, infiltration rates, runoff, and erosion, all of which contribute to potential flooding and contamination risks (Mani et al. 2024). High drainage density in gentle slope areas often correlates with higher infiltration rates and lower runoff, but it also means that contaminants can easily seep into groundwater, creating long-term health risks for both humans and biota (Tedoldi et al. 2016). Contaminants from sewage drains and agricultural runoff that infiltrate the soil pose a significant threat to river water quality, especially in areas where human reliance on rivers is high (Mishra et al. 2022).

The study effectively utilizes available data and advanced GIS-AHP methods, providing valuable insights. While water quality data could be further improved with more advance instruments, and additional factors like climate change could be explored, the approach sets a strong foundation for future river risk assessments and environmental management. Through this research, policymakers and decision-makers can assess the effect of both point and non-point sources of pollution, enabling more targeted management strategies. Identifying the RRZs is critical for targeted mitigation efforts and land-use planning to minimise risks associated with water pollution, floods, and other environmental hazards (Mishra et al. 2022; Akar et al. 2024). In the future, comprehensive management strategies must focus on reducing the pressures in high-risk areas of Asan, Bindal, Rispana, Song, and Suswa rivers to improve their ecological resilience.

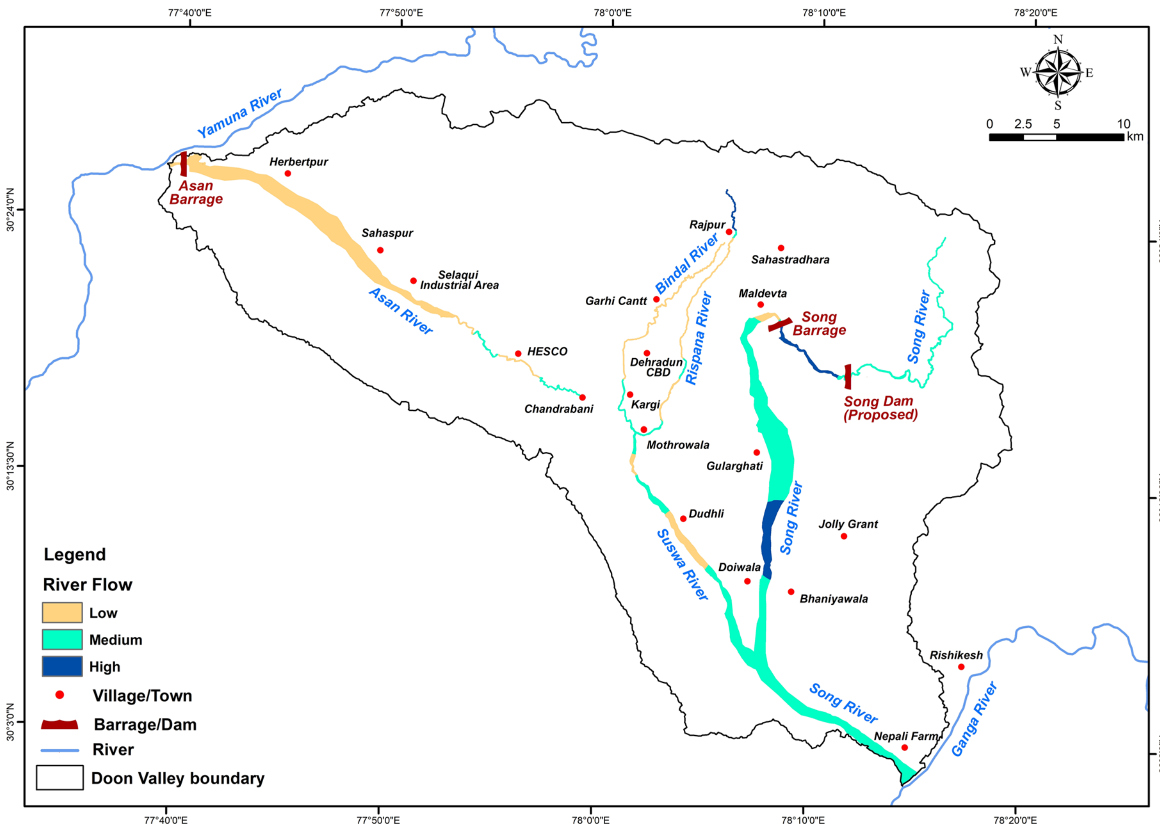


Fig. 14 Flow map of the Doon Valley rivers

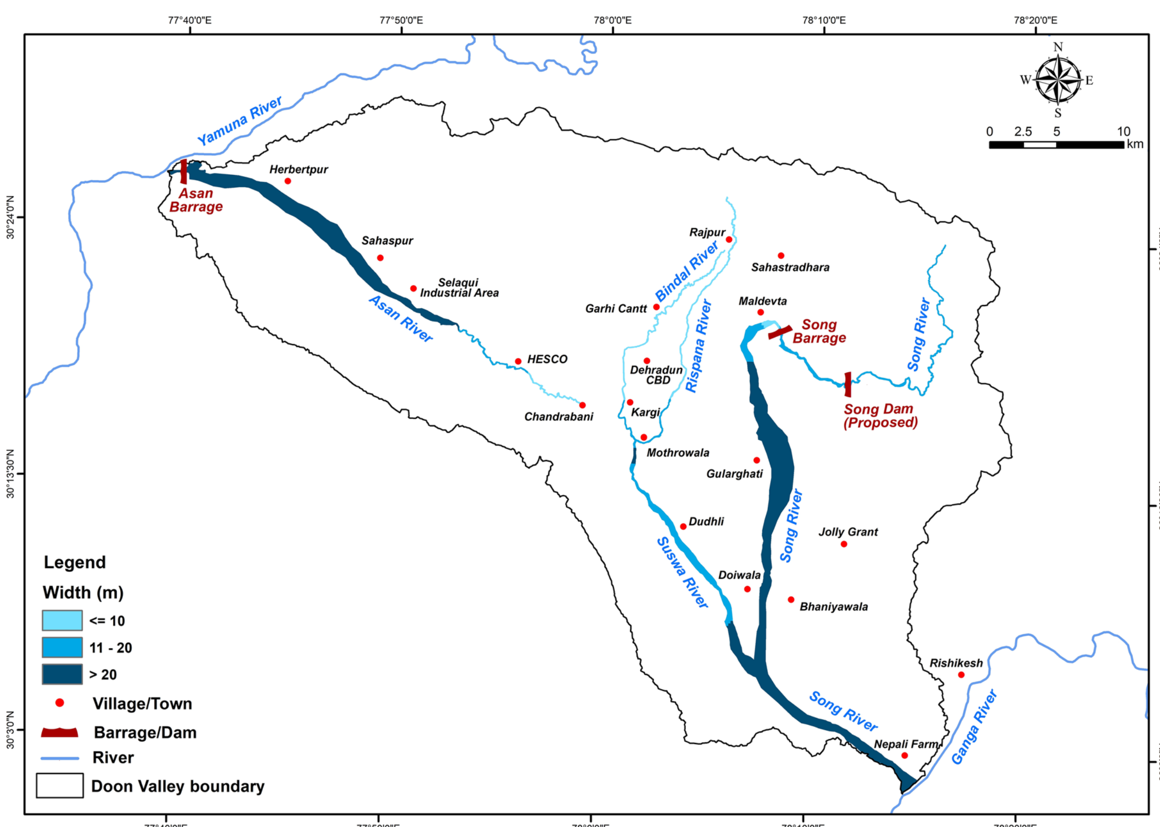


Fig. 15 Width map of the Doon Valley rivers

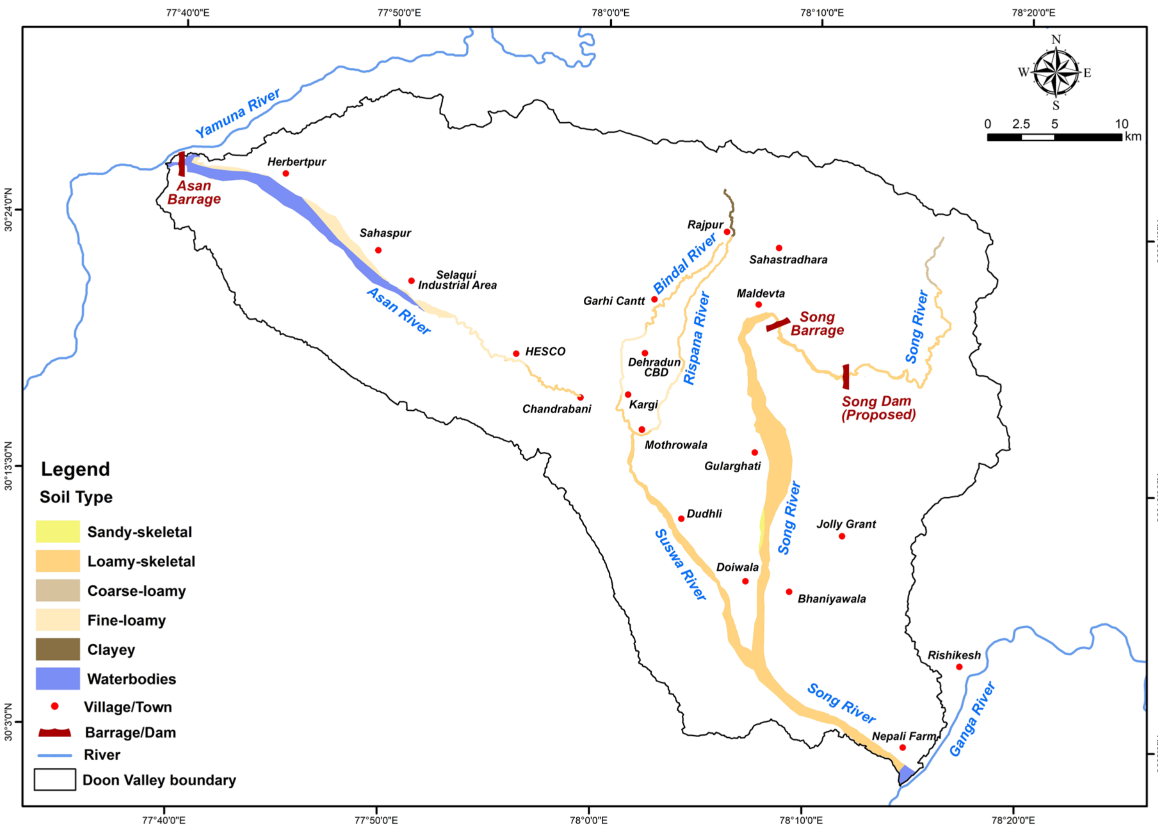


Fig. 16 Soil type map of the Doon Valley rivers

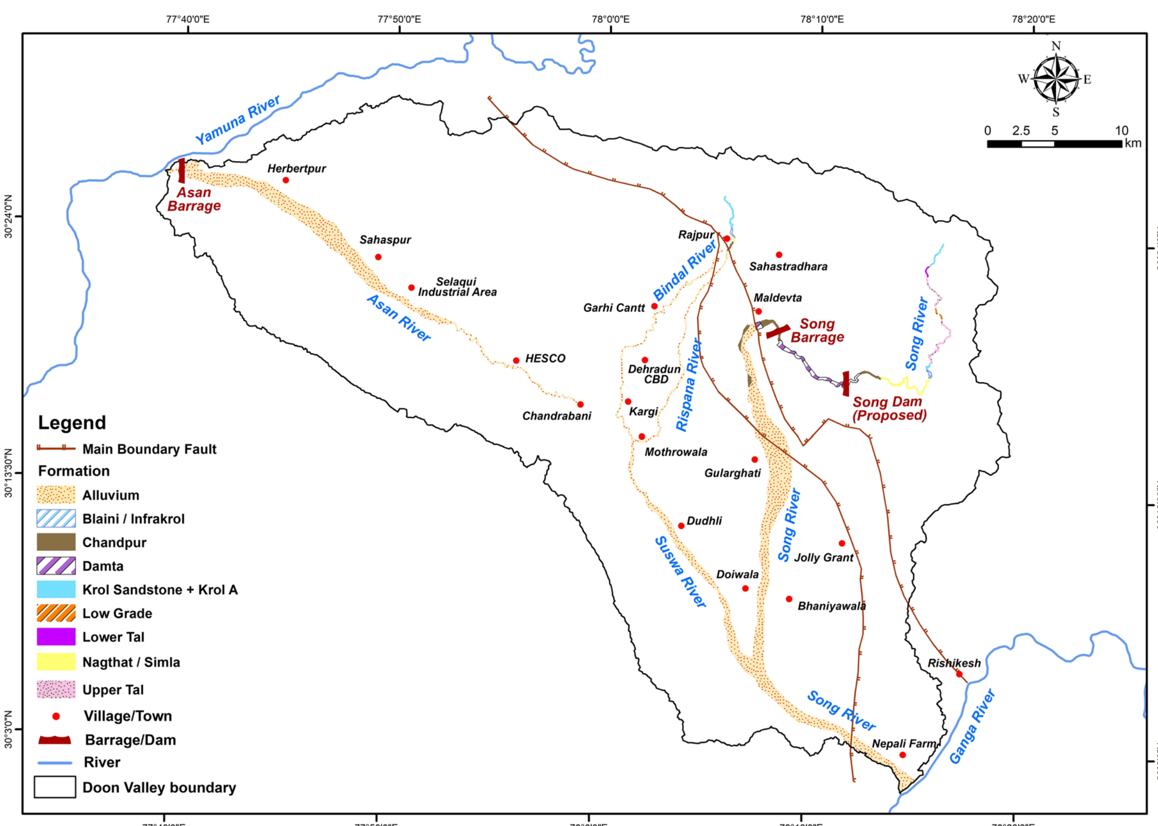


Fig. 17 Geology map of the Doon Valley rivers

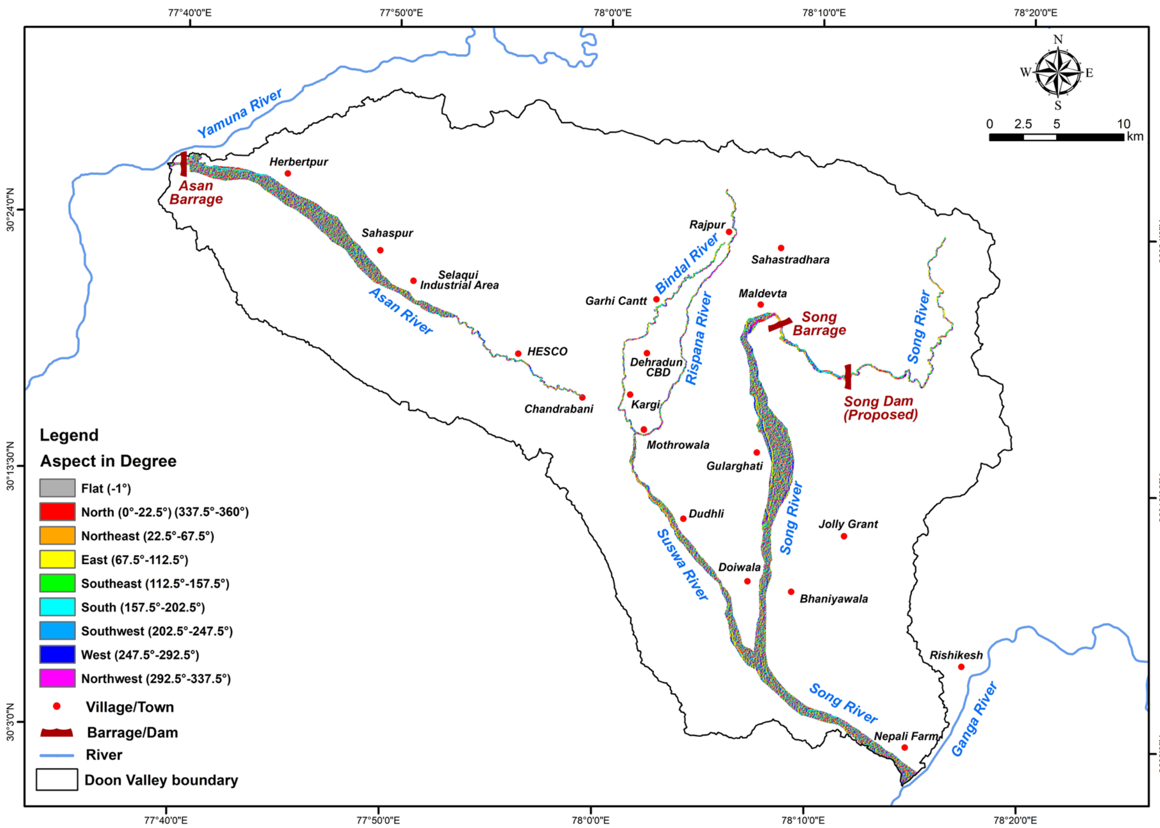


Fig. 18 Aspect map of the Doon Valley rivers

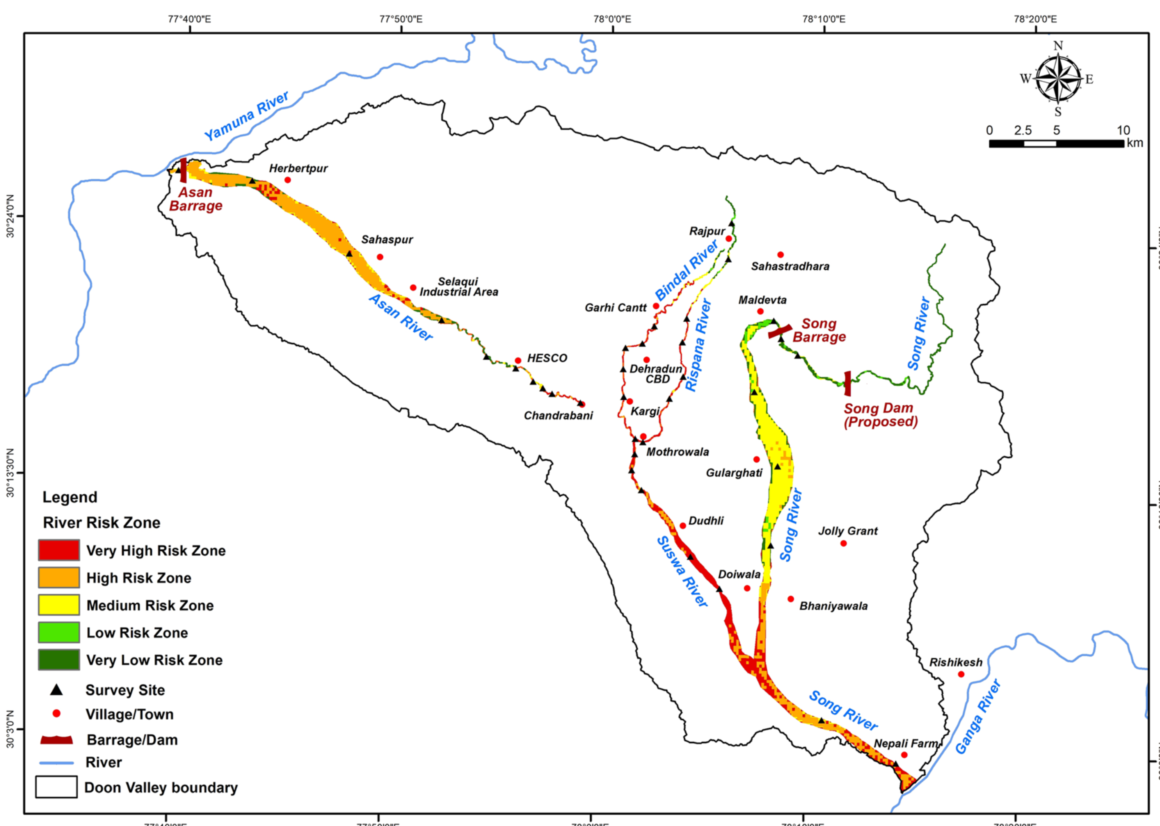


Fig. 19 RRZ map of the Doon Valley rivers

Table 8 Table for RRZ area statistics

S. No	Risk zone	Area in km^2	Area in %
1	Very high-risk zone	10.04	12.45
2	High-risk zone	35.42	43.93
3	Medium-risk zone	27.18	33.71
4	Low-risk zone	2.36	2.93
5	Very low-risk zone	5.63	6.98
Total area		80.63	100

Conclusion

The study demonstrates the growing significance of GIS and AHP-based methods in assessing river risk zones (RRZ) for river systems under environmental stress. The integrated approach in the perspective of Himalayan rivers at Doon Valley, Uttarakhand, India, effectively zoned river segments based on water quality attributes (TDS, conductivity, pH, salinity, and temperature), topographical parameters (slope, aspect, elevation, drainage density, depth, flow, and width), and environmental factors such as LULC, soil type, and geology. The findings reveal that over 56% of the study area falls within high and very high-risk zones, while medium-risk zones cover approximately 33.71%, and the remaining 9.91% are classified as low and very low-risk zones. This underscores the deteriorating situation in the Doon Valley rivers due to inefficient sewage management, land-use changes, agricultural runoff, and urbanization. This assessment highlights the urgent need for improved management strategies, such as enhanced regular monitoring of installed sewage treatment plants (STPs), improved sewage treatment, riverscape restoration by planting indigenous flora species, and stricter land-use regulations to reduce the anthropogenic pressures on these river systems. The RRZ assessment is crucial for planners and policymakers to identify high-risk areas, implement targeted interventions, and ensure river ecosystems' ecological health and sustainability.

Additionally, this proactive, data-driven multi-criteria decision-making analysis is contributing in the WHO's One Health concept, which emphasizes the interconnectedness of human, animal, and environmental health. By effectively managing water resources through data insights, we can protect the environment, thereby supporting the well-being of communities and ecosystems and reflecting the comprehensive approach of One Health. Overall, this study contributes significantly to understanding river dynamics in the Indian Himalayan Region (IHR) and sets a precedent for similar assessments in other rivers.

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Author contribution Conceptualization: Ashish Mani; methodology: Ashish Mani, Maya Kumari; formal analysis and investigation: Ashish Mani; writing — original draft preparation: Ashish Mani; writing — review and editing: Ashish Mani, Maya Kumari, Ruchi Badola; resources: Ashish Mani, Maya Kumari, Ruchi Badola; supervision: Maya Kumari, Ruchi Badola.

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Data availability The authors confirm that the data supporting the findings of this study are available within the article.

Declarations

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