Biological Forum
an International Journal 17(5): 111-123(2025)
ISSN No. (Print): 0975-1130
ISSN No. (Online): 2249-3239

Cultural Significance and Conservation Challenges of Traditional Water Harvesting Systems of Uttarakhand Himalaya: A Critical Review

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(Received: 03 March 2025; Revised: 07 April 2025; Accepted: 02 May 2025; Published online: 24 May 2025)
(Published by Research Trend)

ABSTRACT: Various traditional water harvesting systems such as Naulas, Dharas, Khals, and Guhls in the Himalayan state like Jammu, Himanchal Pradesh and Uttarakhand have ensured the water security for the local communities since ancient time. These systems have traditional, cultural, and architectural importance for the local communities and environment. This review examines the quality of surface and groundwater in the region by evaluating its physical, chemical, and biological characteristics. Climate change and overpopulation have significant impact in decreasing the water level in these systems. They need to conserve with inclusive concept of practice, with traditional method and advance scientific technologies, and policymaking/implementation. The strategies should seek the harmony of the traditional techniques with the contemporary approaches to conservation, strengthening the involvement of local community, and recognizing the value of the practices in the society. Rehabilitation of traditional water harvesting system, frequent monitoring and assessment is essential to ensure water quality and sustainability of these system that significantly contribute to Sustainable Development Goal 6 (SDG 6) at regional level. Further, promoting local communities specially women self-help groups may contribute significantly in the conservation and management of water in Hilly states for sustainability and resilience against the climate change.

Keywords: Himalayan state, Self- Help Group, Sustainable development goal, Traditional Water Harvesting System, Water Security.

INTRODUCTION

Water is a finite and vulnerable resource, necessary for the environment to support life and growth (Hogeboom, 2020). Water plays a crucial role in the expansion of large cities and the formation of communities that are deeply connected to tradition, regional knowledge, and culture. However, over the past few years, concessions on water supplies have become a global issue. Currently, about 2.3 billion people were suffering from inadequate water supply, and about 4 billion people have been without water for at least one month (Tanik and Hanedar 2024). The limited availability of water on the Earth, is ever circulating through water cycle, constitutes the major part of the global system of hydrology (Dastorani and Poormohammadi 2012). The Himalayan region is home to numerous folk knowledge practices that have been tested and evolved over time by indigenous inhabitants living in harmony with nature (Oli and Dhakal 2008). Uttarakhand is one of the fourteen hilly states and Union Territories in northern India, situated in the Western Himalayas. The water problem in the region is complex, involving shortages, pollution, and challenges with its management. Mountain ecosystems in the region are important in providing water supply but experience management challenges that affect both quantity and quality of water (Molden *et al.*, 2013).

Uttarakhand has also seen comparatively poor water management and is severely affected by a water deficit due to overutilization for human and animal use, urbanization, deforestation, and land use change. Fecal bacterial count is on the increase, thus posing health effects to human, especially the underprivileged population with inadequate treated water supply (Sharma, 2014). The improper water treatment increases incidences of waterborne diseases, hence health disparities that are seen to be social inequalities thus affect sensitive populations (Chakraborty, 2017). Contaminated water depletes many public health resources, as millions of people suffer from illnesses linked to a lack of clean water (Greenberg, 2009). Despite the abundant water resources in the region, water scarcity issues persist in many areas due to inadequate water management, heightened population pressure, and climate change (Sharma, 2016). Water is a simple and indispensable necessity for life in any given society for the inhabitants of a particular territory. Conventional rainwater harvesting systems are essential for future water management practice, for improving water access and use, the stimulation of agriculture, and for maintaining water ecosystems in different parts of the world. Therefore, rainwater harvesting remains a central activity towards realizing adequate and quality water supply. Rainwater harvesting systems can reduce water scarcity impacts as they offer a source of water that is not being sourced in many places, as the water table reduces in urban centers (Abraham and Priyadarshini, 2024).

The conservation of rainwater for use in strengthening water supply and demand can help communities with water scarcity, including dry regions. This was in recognition of the fact that conservation of water resources leads to protection of the environment and the provision of potable water that contributes to public health. The knowledge of microbial characterization and activities in rainwater has significant implications for the management of resource to prevent the deterioration of water quality; thus, the importance of further research on this topic is essential (Liu *et al.*, 2024). For centuries, traditional water harvesting systems like naulas (stone-lined wells), Guhls (irrigation canals), dhara (springs), and Khal (ponds) have been used to collect and manage water sustainably in Uttarakhand Himalaya (Fig. 1). Therefore, the present review is comprehensive analysis of existing literature on traditional water harvesting systems with particular focus on its cultural and historical significance in Uttarakhand.

Traditional Water Harvesting System in Uttarakhand. Social and cultural water harvesting systems of Uttarakhand are particularly important for meeting the agricultural and domestic water requirements from the Himalaya, which is rather difficult terrain (Saha *et al.*, 2021). These systems, due to their origin from African indigenous knowledge and practices, have over the past been crucial sources of water in various ways including drinking, livestock, and agriculture (Negi and Kandpal, 2003). Traditionally, the existed water conservation structures in Uttarakhand were used by the inhabitants for drinking purposes along with other uses like irrigation purposes and domestic requirement. These were developed systems to complement some of the existing natural factors, hence making them most efficient in the geographical structures of the Himalayas, which are steep and mostly contain hills (Gupta and Kulkarni 2018). These ancient resources, such as springs, are still in operational and could be a sustainable future water resource (Patni *et al.*, 2022). This water harvesting system were budget friendly and require basic construction material includes stone, wood, and mud like to build and easy to maintain (Bhattacharya, 2015). Historical findings suggest, the conventional ways of making water harvesting structures were also part of cultural and religious beliefs. It was common for many of these structures to be regarded as being of religious significance, and their preservation was therefore a matter of local concern. Nevertheless, owing to increased modernization, most of these traditional water supply methods have faded or else have broken down with the introduction of piped water supply systems. However, present water challenges and climate change realities have fostered some form of appreciation of such systems, hence calls for their restoration.

Several types of traditional water harvesting systems have been used in Uttarakhand, each adapted to the specific needs and geographical features of the region (Table 1). The most prominent ones include Naulas, Dharas, Khal and Guhls.

Naulas (Stepwells). Naulas are mini stepwells for accumulating water from springs. They are usually constructed near the source of a stream where the water is collected in small pits with stones (Rawat, 2021). The steps are constructed to enable people to access water at the water source. Mostly the Naulas are built in a village or on roadsides so that it becomes convenient for the community to use them. They are more commonly found in the Kumaon region as compared to Garhwal and the most prominent feature of Kumaun naulas is longevity. Naulas are flooded water storage structures and have been providing local users with requisite fresh drinking water for centuries. They were designed to perch groundwater and recharge it in the process, and were ideally suited where natural springs were common. Such traditional structures have contributed much to water governance to make safe water access available in many areas (Singh *et al.*, 2022). There are numerous examples of sustainable technology that are still in use today. Around the 7th century A.D., the Badrinathji-ka-naula is arguably the oldest naula still in use. Other significant ones are the oldest one in Almora district, Syunrakot Naula (14th or 15th century), Patan-ka Naula (14th or 15th century), and Jahnvi Naula (1263 A.D.) in Gangolihat (Baker, 1997). The longevity of Kumauni naulas can largely be attributed to the dedicated maintenance efforts of local communities. Throughout history, naulas were clearly community property until around 30 years ago. Typically, there were no specific management guidelines. In October 1938, the ruler of Tehri Garhwal took a significant step by introducing the Prant Panchayat Vidhan, marking an important development in local governance and administration (PSI, 2009).

Dharas (Water Springs). Dharas or Munguru are types of naturally occurring water sources that receive from the ground without passing through a pipeline (Fig. 1 a&b). These springs are common in hilly areas and have been an important source of water for villages in Uttarakhand. Dharas used to be considered as sacred structures, and their construction was protected by the community like the Naulas. People collect water from these springs for drinking and household purpose. Dharas maintain groundwater levels and provide clean water even during dry seasons. In hilly areas these water bodies are the only sources of water supply such as Parda dhara and Sipahi dhara in Nainital and perennial dhara next to a Shiva shrine in Gopeshwar (Chopra, 2003).

Khal (Man-made Ponds). Khal is small, low-depth ponds used as conventional rainwater management system for rainwater storage. These constructions are carried at higher ground with a purpose of harvesting water during the monsoon and used for irrigation and domestic purposes. It slows rainwater flow by reducing its speed, helping it absorbs into the ground, and minimize runoff thus prevents soil erosion and maintain the soil moisture, thus improving agriculture (Suri and Mamta 2022). In Pauri district, around 70 well-known khals have been identified specially designed to collect rain water (PSI, 2009).

Guhls (Irrigation Channels). Guhls are the irrigational streams used in conveying water from rivers or streams to fields in hilly areas. They are built with a gentle slope, allowing water to flow easily from higher places to the fields below. These channels are usually dug manually, creating shallow trenches that guide the water flow. These guhls have a capacity of fifteen to hundred liters of water per second and range in length from one to fifteen kilometers (Bhattacharya, 2015). Guhls are an efficient water source to terraced fields in hilly areas for irrigation purposes. Communities often maintain them together to ensure a steady water supply for their crops (Banskota, 1999).

Structural significance of traditional water harvesting system. Naulas consist of sharply defined components that have a practical form and are used nowadays (Fig. 2). The structure is constructed as an inverted trapezoid, and the tank is three-sided and covered to shelter water. The fourth side does not have any roof, and there are some stairs that lead toward the water tank for convenient access. The lowest step is the smallest (1 × 1 ft), and the highest step (8 × 8 ft) in size (Chopra, 2003). A pillared verandah is constructed around the naula, and on the exterior part of it, more often ink carvings are made, enhancing the cultural aspect of the naula. These structures are designed to exclude animals and other biotic intrusions, thereby minimizing the risk of water contamination (Rawat and Sah 2009).

Dharas are natural springs that have their own water source on the ground. They are formed when water stockpiled underground in layers and moves out through the fracture zones from the rocks. In some rural areas with insufficient water supply, it is the only water source for drinking and domestic purposes (Admin, 2021).

Khals are excavated water bodies that are constructed on hill slopes for harvesting water from upland runoff. These ponds are simply dug out to small depressions and covered with stone or clay to avoid water evaporation. The harvested water is used for irrigation, livestock, and recharging of groundwater. Dimensions of khals may range from 5 to 10 meters in length, 5 to 7 meters in width and 0.75 to 1 meter in depth (Patil *et al.*, 2018).

The volume of Khal can be theoretically calculated as $V = E.C.R.A/f$

Where, V= volume of Khal; C = surface run-off coefficient; R = Maximum rainfall in a day; A = catchment area; E = efficiency factor; f = number of times Khal is filled (generally 1.5 to 3) (Patil *et al*., 2018).

Guhls are traditional irrigation channels used to divert water from rivers or streams to agricultural fields. Generally, they are farmer managed irrigations systems (FMIS). They follow the natural slopes of hills to avoid erosion. The guhl in Maletha village, Tehri Garhwal, is one of the most renowned guhl in Uttarakhand. It is based on FMIS and constructed by carving a 100-meter tunnel through solid rock, situated about 350 meters from its diversion point (PSI, 2009). Traditionally, guhls are useful in supplying water to the agricultural land, particularly in the hills where farmers engaging in terrace farming (Sharma *et al*., 2023).

Cultural significance of traditional water harvesting system. Naulas, Dharas, Khal, and Guhls are the traditional water resources that are used in day-to-day life and farming practices in the region of Uttarakhand. Community people consider these traditional water resources equivalent to the deities thus ensure the maintenance and hygiene. According to the Vaastu legislation of the deities, they were also constructed under the specific Vastu Vidhaya (Joshi, 2019). Dharas are often recognized by small shrines dedicated to local deities inside or near the spring. Sculptures of Lord Vishnu or any local deity are usually carved onto the walls of the Naula or Dhara to declare it a sacred site and prevent it from being polluted (Joshi, 2018).

It is local tradition to decorative Naulas in every village in the Kumaon region. Ek Hathiya ka Naula, Syunrakot Naula, Naga Naula, Jahnavi Naula, Sidh Naula, Hathi Naula, and Badi Bagheeche Naula are some famous Naulas that are not only known for their unique taste but also for artistic architecture (Fig. 2). In ancient times, trees were strategically planted near various naulas to enhance groundwater recharge and protect the integrity of these water sources. These tree species include oak (*Quercus leucotrichophora*), kharik (*Osmanthus fragrans*), peepal (*Ficus religiosa*), bargad (*Ficus bengalensis*), timil (Ficus pathmala), dudhaila (*Ficus nemoralis*), padam (*Prunus cerasoides*), amla (*Emblica officinalis*), shahtut (*Morus alba*), and utis (*Alnus nepalensis*). They contribute significantly in ecological balance and water conservation in the area (Rawat and Sah, 2009). Thus, majority of traditional water harvesting system like Naulas are functionally and culturally similar, with different architecture and equal significance. Despite their significant role in water conservation, traditional systems such as *naulas*, *dharas*, *khal*, and *guhls* have been largely neglected in recent years due to the adoption of modern water and irrigation technologies. Consequently, these systems have deteriorated over time—their structures have collapsed, channels have become silted, and water sources have been compromised. The contributing factors include deforestation, rapid urbanization, and the overextraction of groundwater (Jain et al., 2024).

Physico-chemical and microbiological characteristics of traditional water harvesting system.

The physiochemical characteristics of different springs like Teendhara, Bidakot, and Nainital of Garhwal and Kumaon divisions found prominence differences with the BIS standard (Table 2). The pH values of reported springs ranged from 6.5-8.5 which is considered suitable for drinking. However, some areas such as Bhaktiyana and Kothar, have exceeding the mineral content (electrical conductivity) above the desirable limit (500 μs/cm), thus lead to poor taste. Total Dissolved Solids (TDS) also pose concern which was documented above the desirable limit (500 mg/l) subsequently affecting the water quality in various region like Kothar Dhara and Hanuman Mandir Dhara in the Garhwal region. The regional significant difference in nitrates and chlorides ion content in water bodies require the periodic monitoring. Elevated concentrations of heavy metals in the springs of Kumaon and Garhwal adversely impact the potability and overall quality of water in these traditional harvesting systems (Table 2).

In the Kumaon region, most of the studied springs exhibited low levels of contamination. However, the Kulgarh spring showed a significantly high iron concentration (3 mg/L), which exceeds the Bureau of Indian Standards (BIS) permissible limit of 1.0 mg/L. In contrast, springs in the Garhwal region generally exhibited moderate iron levels (0.066–0.068 mg/L), while copper and lead concentrations remained within the recommended limits in key urban areas such as Haridwar, Vikasnagar, and Mussoorie. Nonetheless, high iron concentrations (0.4 mg/L) exceeding the BIS desirable limit were reported in Srikot and Supana. Manganese levels were comparatively higher (0.1 mg/L) in the spring near Satyanarayan Temple in Nainital, aligning with the BIS desirable limit (Table 3). Microbiological assessments revealed coliform contamination in traditional water harvesting systems in springs of Garhwal (Bhaktiyana, Kothar, and Joshimath), though *E. coli* was absent. According to BIS guidelines, both coliforms and *E. coli* should be absent in potable water. The presence of microbial contamination in several springs in the Garhwal region indicates a potential public health concern and underscores the need for regular monitoring and improved water treatment measures.

Threat to Natural water resources. Thakur and co-workers reported over 900 springs, distributed from 222 m to 2600 m above sea level in Uttarakhand. Urbanization, shrinking recharge zones, variation in rainfall pattern and surface runoff are the major threat to traditional water resources specially in Nainital and Udham Singh Nagar districts (Thakur *et al*., 2022). The changing climatic condition affects the resource water level in the region. The significant decrease in spring water level was recorded in Kumaun region (299 springs) followed by Chamoli (182 springs) and Uttarkashi (136 springs) in the Garhwal region (Fig. 3). The springs water scarcity data in Uttarakhand is presented in Table 4. Water scarcity leads to livelihood challenges, health issues on local communities. For example: Amni-ka-Dhara, a historically significant perennial spring located in the Garhkot watershed of the Tehri Garhwal district, ceased to flow after the 1991 Uttarkashi earthquake. In addition to seismic activity, the degradation of forest cover has further contributed to the decline of such springs by reducing groundwater recharge and the landscape's water retention capacity as reported in Pauri, which once sustained itself through an ancient dhara, now faces acute water scarcity (PSI, 2009).

Impact of Climate change. The variation in weather pattern, rainfall and higher temperatures contributing to disasters that affect agriculture, food security, people welfare, and the ecosystem supporting systems (Tyagi *et al.*, 2022). Approximately 36 % of the springs have declared dried, permanent stream sources have vanished, and the water flow in springs as well as streams has drastically decreased in the last 20 years (Tewari and Tewari, 2023). The traditional water sources like naulas and dharas in Himalayan states contributed significantly as water resource. Therefore, restoration and conservation of these natural resources is crucial for the sustenance of local communities. Significant decrease was reported in spring water recharge, water availability in naulas and dharas due to increased temperature, reduced snowfall and unpredictable rainfall patterns (Rautela and Karki 2015). The drop-in water flow across different districts in Uttarakhand is presented in (Table 5). Some areas like Pauri showed maximum decline in water discharge with 185 schemes followed by Tehri (89) and Champawat (54) district. Concerning the impact intensity, most of the schemes have recorded a decrease of 75-90% reduction which indicate poor availability of water (Table 5). This underlines the necessity of intensive water planning and tackling of natural water resource with reference to climate change.

Conservation Efforts: Governmental, non-governmental and scientific initiatives. In hilly regions like Uttarakhand, local people have been using these water resources (Naulas, Dharas, Khal, and Guhls) since ancient time fulfill the water demand. These resources served for water demand for domestic consumption and support lives in hilly areas. Nevertheless, the proficiency of these systems has declined due abandonment as well as changes in the environment. Pertaining to the issues, the government, non-governmental organizations (NGOs), and other scientific organizations have initiated some measures with the aim of rehabilitating and conserving them to continue to support the people that rely on them (Table 6).

Governmental Initiatives.

The Government of Uttarakhand has undertaken several programs like Jal Jeevan Mission to focus on water conservation and rural development (JJM, 2024). Another key intervention is the *National Mission for Clean Ganga* (NMCG, 2024), which aims to restore the ecological health of the Ganga River and its tributaries. This mission also supports the revival of traditional water harvesting systems, contributing to watershed sustainability. Additionally, state agencies such as the Uttarakhand Jal Sansthan are actively working to restore traditional water harvesting structures like Naulas and Dharas, which historically played a vital role in groundwater recharge and community water supply. The Ministry of Environment, Forest and Climate Change (MoEFCC) has also implemented afforestation programs following a triad approach in forested areas, emphasizing community participation and ecological restoration (PIB, 2022).

Non-Governmental Initiatives. Various non-governmental organizations (NGOs) are actively involved in the restoration of the traditional water harvesting structures in the region (Table 6). Many awareness programs have been conducted regarding the spring inventory and impact monitoring through the Spring Atlas of Uttarakhand by Central Himalayan Rural Action Group (CHIRAG). The Naula Foundation is also involved in rehabilitation of Naulas to ensure the maintenance by indigenous people. People's Science Institute (PSI), Himmotthan, and the Himalayan Environmental Studies and Conservation Organization (HESCO) are working to support community-based waters management systems. They engage with people, authorities, and scientists to achieve the preservation of Naulas, Dharas, and other traditional structures. These organizations not only create awareness, but also educate the societies against the preservation of these natural water resources, cultural and environmental-temporal landscape in the region.

Scientific Initiatives

Researchers have been studying the effectiveness and sustainability of the natural water resources. To ensure safe drinking water, Development Alternatives (World's first social enterprise dedicated to sustainable development) has developed a fast, easy to operate, robust and reliable water testing kit Jal-TARA to check physico-chemical and biological parameters of water (Bhardwaj, 2002). In addition, nanobubble technology may presents eco-friendly techniques to improve the water quality and management practices (Hoque *et al.*, 2025, Esmaili, 2025). Further, to support sustainable water resource planning, GIS mapping of water harvesting system is necessary to track the impact of environmental factors. This technology allows to identify the areas most suitable for rainwater harvesting by considering different factors including land use, soil type, runoff, and slope of the area (Alene *et al.*, 2022). Therefore, development and validation of scientific methods is must to visualize and manage water resources more efficiently, upgradation of traditional techniques to meet modern needs (Abbas *et al.*, 2024). By using these modern scientific tools and knowledge, traditional water harvesting systems continue to support communities in Uttarakhand.

Role of Community and Women Self-Help Groups.

Women play a crucial role in the conservation of traditional water resources, attributed to their close association with natural ecosystems and their in-depth knowledge of local resource availability (Pal and Pooja, 2024). Specially the Self-Help Groups (SHGs) significantly contribute to water management through the exchange of indigenous knowledge and collective resource utilization, thereby enhancing community health and promoting environmental sustainability (Vijayalakshmy *et al.*, 2023). SHGs serve as vital platforms for fostering community participation, encouraging cooperative behavior, and advancing sustainable resource management practices.

The involvement of women in traditional water management not only enhances natural resource governance but also contributes to the social development of local communities (Kumar and Kumar, 2024). Women actively participate in decision-making processes and in the formulation of rules related to water governance during community meetings and local forums (Akolgo and Ayentimi, 2020). Traditionally, the responsibility of water collection for domestic use has primarily fallen on women, particularly in mountainous regions where water sources are often distant and difficult to access. On average, women spend between two to four hours daily fetching water; in some remote areas, this can extend to as much as eight hours. Annually, a woman may walk over 3,000 kilometers solely for water collection (Chauhan, 2010). The case study from Uttarakhand, located in the Indian Himalayas, illustrates how women's Self-Help Groups (SHGs) effectively coordinate community efforts to conserve and revitalize traditional water systems.

Maya Verma from Chanoli, Almora District. Maya Verma, in her village Chanoli along with others woman came together and helped to rejuvenate Naulas and Dharas. They have been restoring the water sources of 15 villages since October 2017, so that they remain filled with water throughout the year. Over the years, they maintain these water resources by frequent cleaning of the debris, mud and silt build up. They also planted broad-leaved trees and drew upon indigenous knowledge to maintain the working order of Naulas as a resource on which their communities rely for drinking water (Roy and Ghosh 2020). This case study significantly reflects the crucial role of women in the preservation of traditional water harvesting systems. Their dedication helps maintain these vital resources, ensuring water security for their communities.

Tools and Techniques used in Water quality Testing. Water quality testing is crucial to ensure the safety and quality of water sources. Various methods and equipment are used to evaluate different water parameters including physio-chemical and biological characteristics (Table 7). The Laser spectroscopy is used to detect organic materials, while conductivity is used to measure total dissolved solids (Tian *et al.*, 2023). For the chemical analysis, ion chromatography is used to analyze anions such as nitrates and sulfates whereas microbiological assessment is also required to detect the absence/absence of pathogenic bacteria (Kaynar *et al.*, 2022). The Nutrient parameters include the measurement of pH, turbidity, dissolved oxygen (DO) through the portable field-testing kits, while spectrophotometers are employed for nitrate, sulfate, and fluoride testing. The quantitative assessment of heavy metals (iron and lead) is analyzed through atomic absorption spectrophotometers (AAS). Microbial tests, including the detection of bacteria like coliform and *E. coli*, rely on membrane filtration techniques or portable biological kits for on-site analysis. Portable devices are especially essential for field surveys of water quality, as they allow for the rapid assessment of nutrients, metals, and microorganisms. These devices offer convenient with immediate results and provide real-time information, which is critical for timely decision-making and adopting effective and efficient steps for the management of water quality in the hilly areas. Thus, portable testing kits may contribute significantly to ensure the regular monitoring of water quality and identification of associated risks are addressed promptly.

Application of Remote sensing (RS) and Geographical Information System (GIS) in traditional water harvesting system. The integrated use of remotely sensed data, global positioning system, and geographic information systems together have been extensively used for mapping, monitoring and analyzing a variety of natural resources (Dutta et al., 2024). These tools also provide better scope for decision making and developing plans for management applications. Remote sensing techniques can be used to monitor water quality parameters like temperature and suspended sediments (turbidity) (Kumar *et al.*, 2015). Spatial and temporal remote sensing information needed to monitor changes in water quality parameters. Study reaved that RS and GIS techniques are essential for understanding current status of the natural springs of Uttarakhand. They also delineated springshed, and then proposed a comprehensive springshed management plan for the restoration of the natural springs in the region. Detailed analysis was done using ArcGIS and QGIS software in order to create comprehensive maps that show the location and catchment areas of springs, providing important information about the geological structures governing water flow, availability, and even sustainable water management practices (Thakur *et al.*, 2022). The tools and techniques applied in geospatial studies of springs in Uttarakhand and similar regions is given in Table 8. Groundwater potential sites for water harvesting in the district Dehradun, Uttarakhand, India were identified using remote sensing and GIS techniques. Terrains characteristics, normalized difference vegetation index (NDVI), and land use land cover (LULC) mapping were done from satellite imagery like Landsat 9 and ALOS PALSAR in the ArcGIS environment. The different thematic layers like geomorphology, lithology, slope, soil, lineament density, drainage density, and NDVI were allocated a proportional weight through weighted overlay analysis, to delineate the prospective groundwater map of the study area. Then the land was classified into high, moderate, and low groundwater potential zones depicting the efficacy of these techniques in Uttarakhand for water resources and springs management (Thakurlal *et al.*, 2023).

Table 1: Natural Water Sources in Uttarakhand (Gauniya, 2020).

Sr. No.	Name	Source	Purpose/uses
1.	Naula and Dhara	Natural Water sources	Drinking, Domestic, Irrigation,
2.	Gadhera	Stream	Drinking, Irrigation
3.	Gaad	River	Drinking, Domestic, Irrigation, Hydropower
4.	Guhls	Waterfall	Irrigation
5.	Dyo	Rainfall	Rainwater Harvesting
6.	Tal/ Khal/Pokhar/ Simar	Ponds and Lakes	For Animals drinking

Table 2: Physiochemical analysis of natural water springs from various locations in Garhwal and Kumaun region in Uttarakhand Himalaya.

Region	Location/ Name of Spring	Physiochemical properties															Reference
		pH	Turbidity (NTU)	EC (µs cm^{-1})	DO (mg l^{-1})	BOD (mg l^{-1})	TDS (mg l^{-1})	Salinity (mg l^{-1})	F^-(mg l^{-1})	Alkalinity (mg l^{-1})	TH (mg l^{-1})	Ca (mg l^{-1})	Mg (mg l^{-1})	NO_3(mg l^{-1})	Cl^-(mg l^{-1})	SO_4(mg l^{-1})	
Garhwal	Teendhara	7.1	-	95	-	-	61	-	-	50	76	11	12	ND	ND	3	Negi *et al.* (2007)
	Bidakot	7.1	-	168	-	-	108	-	-	66	100	22	11	10	2	3	
	Karas	6.9	-	93	-	-	60	-	-	52	130	18	20	ND	ND	ND	
	Bhaktiyana	7.1	-	568	-	-	364	-	-	170	276	71	24	7	18	116	
	Kothar	7.2	-	529	-	-	338	-	-	168	262	67	23	ND	4	20	
	Gulabrai	7.1	-	134	-	-	86	-	-	70	120	19	18	ND	ND	4	
	Kamera	6.9	-	82	-	-	52	-	-	46	122	25	14	ND	ND	2	
	Chatwapipal	7.4	-	176	-	-	113	-	-	82	92	22	9	ND	ND	7	
	Bhatoli	7.4	-	290	-	-	185	-	-	158	158	42	13	ND	ND	7	
	Maithana	6.7	-	73	-	-	47	-	-	36	108	20	14	ND	ND	4	
	Batula	6.8	-	62	-	-	40	-	-	40	102	18	14	ND	ND	3	
	Joshimath	6.9	-	232	-	-	148	-	-	60	128	24	17	21	6	13	
Garhwal	Kolun Dhara	6.9	-	596	2.9	-	-	-	-	-	246	-	-	5	58	-	Singh *et al.* (2014)
	Beega Dhara	6.9	-	516	2.5	-	-	-	-	-	220	-	-	6	58	-	
	Kamleshwar Dhara	6.9	-	684	2.8	-	-	-	-	-	267	-	-	8	68	-	
	Hanuman Mandir Dhara	7.1	-	530	3.05	-	-	-	-	-	211	-	-	6	59	-	
	Kothar Dhara	7.2	-	510	3.2	-	-	-	-	-	218	-	-	9	60	-	
Kumaon	Dhargara	7.3	-	-	-	-	320	190	-	-	156	-	-	1	10	-	Bisht *et al.* (2018)
	Ghatghar	6.4	-	-	-	-	110	80	-	-	48	-	-	Nil	202	-	

	Salkuli	7	-	-	-	-	200	125	-	-	96	-	-	1	32	-	
	Kulgarh	7.5	-	-	-	-	170	100	-	-	96	-	-	1	16	-	
	Mouna Talla	6.5	-	-	-	-	110	70	-	-	96	-	-	Nil	16	-	
	Dansil	6.4	-	-	-	-	110	80	-	-	48	-	-	1	20	-	
Garhwal	Haridwar	7.8	-	-	-	-	-	-	-	275	252	-	-	-	154	198	Gaur *et al.* (2011)
	Vikasnagar	7	-	-	-	-	-	-	-	328	282	-	-	-	196	153	
	Mussoorie	7.4	-	-	-	-	-	-	-	336	329	-	-	-	121	130	
	Dehradun	7.2	-	-	-	-	-	-	-	322	291	-	-	-	289	170	
	Dakpathar	7.1		-	-	-	-	-	-	322	272	-	-	-	185	152	
Garhwal	Sweet	7.2	0.65	-	-	-	338	-	0.2	160	192	58	12	1.2	14	18	Bhandari and Bisht (2022)
	Srikot	7.5	1.55	-	-	-	540	-	0.4	254	280	92	12	2.1	14	24	
	Kothar	7.3	0.52	-	-	-	349	-	0.4	152	192	55	14	1.2	14	18	
	Hanuman Temple	6.6	0.81	-	-	-	414	-	0.3	148	208	61	14	4.5	28	44	
	Kamleshwar Dhara	6.7	0.95	-	-	-	480	-	0.03	256	280	99	9	1.2	48	46	
	Bhaktiyana	6.9	1.21	-	-	-	460	-	0.7	256	284	96	11	1.4	36	43	
	Ufhlda	7.1	1.36	-	-	-	502	-	0.6	260	296	99	12	0	20	47	
	Supana	7.7	0.96	-	-	-	236	-	0.3	106	124	37	8	1.2	7	11	
	Barktot	7.6	1.72	-	-	-	314	-	0.4	228	260	91	11	0.2	16	8	
	Naithana	7.7	1.12	-	-	-	378	-	0.4	172	196	60	11	1.6	11	16	
	Kirtinagar	7.2	1.46	-	-	-	426	-	0.1	244	280	99	12	0.1	32	31	
Kumaon	Nainital (Near Nishant Hostel)	6.8	-	-	3.01	0.6	10	-	-	-	-	100	-	1	-	-	Negi *et al.* (2022)
	Nainital (Near Ramleela Ground)	7	-	-	3.18	0.7	12	-	-	-	-	34	-	0.2	-	-	
	Nainital (Near Satyanarayan Temple)	7.3	-	-	3.17	0.3	14	-	-	-	-	186	-	0.7	-	-	
	Nainital (Near Vimarsh Cottage)	7	-	-	2.86	1.4	10	-	-	-	-	124	-	0.7	-	-	
	Nainital (Near Bhotiya Band)	6.5	-	-	8.74	1	13	-	-	-	-	108	-	0.4	-	-	
	Nainital (Near Masjid)	6.8	-	-	2.06	1	13	-	-	-	-	94	-	0.3	-	-	
	Nainital {Chuna Dhara (A)}	7	-	-	3.12	0.4	11	-	-	-	-	101	-	1	-	-	
	Nainital {Chuna Dhara (B)}	7.1	-	-	2.95	1.2	9	-	-	-	-	101	-	0.2	-	-	
Kumaon	Champawat	7.7-8.2		127-222	-	-	-	-	-	-	70-110	16-4	5-7	-	5-9	-	Bussa *et al.* (2009)
Kumaon	Bageshwar (Banri)	7.4	0	434	-	-	232	-	0.3	129	-	32	38	7	64	-	Azam *et al.* (2022)
	Bageshwar (Manikhet)	8.0	0	553	-	-	287	-	0.5	225	-	30	55	5	36	-	
	Bageshwar (Darsu Aare)	7.5	0	267	-	-	141	-	0.5	215	-	44	13	4	20	-	
	Bageshwar (Kukudagaad-Bahuli)	7.3	0	37	-	-	19	-	0.4	89	-	12	6	3	50	-	
	Bageshwar (Kamedi)	7.4	0	142	-	-	73	-	0.7	82	-	26	11	3	52	-	
	Bageshwar (Shri Naula Dhaara)	7.9	0	405	-	-	212	-	0.5	160	-	40	43	10	87	-	
	Bageshwar (Bilauana)	8.4	0	348	-	-	185	-	0.5	190	-	50	30	5	53	-	
	Bageshwar (Bhaniya Dhaar -1)	7.8	0	115	-	-	59	-	2.5	119	-	18	19	2	29	-	
	Bageshwar (Bhaniya Dhaar -2)	7.8	0	78	-	-	39	-	0.4	68	-	14	12	4	26	-	
	Bageshwar (Bhitaal Gaon)	7.4	0	121	-	-	61	-	0.5	90	-	2	14	5	53	-	
	Bageshwar (Nye Basti Chaurasi)	8.0	0	352	-	-	184	-	0.6	157	-	38	15	2	54	-	
BIS 10500:2012 Specification	**Desirable Limit**	6.5-8.5	1	-	-	-	500	-	1	200	200	75	30	45	250	200	BIS (2012)
	Permissible Limit	NR	5	-	-	-	2000	-	1.5	600	600	200	100	NR	1000	400	

Abbreviation: EC- Electrical Conductivity; DO- Dissolved Oxygen; BOD- Biochemical Oxygen Demand; TDS- Total Dissolve Solids; T.H.- Total Hardness; ND- Not Determined; NR- No Relaxation

Table 3: Heavy metal status in natural water springs form various locations in Garhwal and Kumaun region in Uttarakhand Himalaya.

Region	Location/ Name of Spring	Heavy Metals									Reference
		Total Iron (mg/l)	Aluminum (mg/l)	Barium (mg/l)	Copper (mg/l)	Cobalt (mg/l)	Manganese (mg/l)	Lead (mg/l)	Cadmium (mg/l)	Chromium (mg/l)	
Garhwal	Haridwar	0.066	0.056	0.057	0.022	0.06	0.052	0.084	0.131	0.094	Gaur *et al.* (2011)
	Vikasnagar	0.068	0.058	0.078	0.022	0.062	0.058	0.09	0.132	0.096	
	Mussoorie	0.062	0.056	0.079	0.021	0.064	0.054	0.088	0.133	0.096	
	Dehradun	0.067	0.056	0.079	0.021	0.064	0.053	0.088	0.133	0.096	
	Dakpathar	0.064	0.056	0.078	0.018	0.06	0.054	0.09	0.13	0.098	
Garhwal	Sweet	0.12	-	-	-	-	-	-	-	-	Bhandari and Bisht (2022)
	Srikot	0.4	-	-	-	-	-	-	-	-	
	Kothar	0.04	-	-	-	-	-	-	-	-	
	Hanuman Temple	0.18	-	-	-	-	-	-	-	-	
	Kamleshwar Dhara	0.15	-	-	-	-	-	-	-	-	
	Bhaktiyana	0.12	-	-	-	-	-	-	-	-	
	Ufhlda	0.14	-	-	-	-	-	-	-	-	
	Supana	0.4	-	-	-	-	-	-	-	-	
	Barktot	0.08	-	-	-	-	-	-	-	-	
	Naithana	0.3	-	-	-	-	-	-	-	-	
	Kirtinagar	0.14	-	-	-	-	-	-	-	-	
Kumaon	Nainital (Near Nishant Hostel)	-	-	-	-	-	0.12	-	-	-	Negi *et al.* (2022)
	Nainital (Near Ramleela Ground)	-	-	-	-	-	0.1	-	-	-	
	Nainital (Near Satyanarayan Temple)	-	-	-	-	-	0.1	-	-	-	
	Nainital (Near Vimarsh Cottage)	-	-	-	-	-	0.06	-	-	-	
	Nainital (Near Bhotiya Band)	-	-	-	-	-	0.11	-	-	-	
	Nainital (Near Masjid)	-	-	-	-	-	0.01	-	-	-	
	Nainital {Chuna Dhara (A)}	-	-	-	-	-	0.03	-	-	-	
	Nainital {Chuna Dhara (B)}	-	-	-	-	-	0.03	-	-	-	
Kumaon	Dhargara	Nil	-	-	-	-	-	-	-	-	Bisht *et al.* (2018)
	Ghatghar	Nil	-	-	-	-	-	-	-	-	
	Salkuli	0.01	-	-	-	-	-	-	-	-	
	Kulgarh	3	-	-	-	-	-	-	-	-	
	Mouna Talla	0.01	-	-	-	-	-	-	-	-	
	Dansil	Nil	-	-	-	-	-	-	-	-	
Kumaon	Bageshwar (Banri)	0.05	-	-	-	-		-	-	-	Azam *et al.* (2022)
	Bageshwar (Manikhet)	0.05	-	-	-	-		-	-	-	
	Bageshwar (Darsu Aare)	0.04	-	-	-	-		-	-	-	
	Bageshwar (Kukudagaad-Bahuli)	0.05	-	-	-	-	-	-	-	-	
	Bageshwar (Kamedi)	0.06	-	-	-	-	-	-	-	-	
	Bageshwar (Shri Naula Dhaara)	0.05	-	-	-	-	-	-	-	-	
	Bageshwar (Bilauana)	0.1	-	-	-	-	-	-	-	-	
	Bageshwar (Bhaniya Dhaar -1)	0.03	-	-	-	-	-	-	-	-	
	Bageshwar (Bhaniya Dhaar -2)	0.02	-	-	-	-	-	-	-	-	
	Bageshwar (Bhitaal Gaon)	0.02	-	-	-	-	-	-	-	-	
	Bageshwar (Nye Basti Chaurasi)	0.04	-	-	-	-	-	-	-	-	
BIS 10500:2012 Specifications	Desirable Limit	0.3	0.03	0.7	0.05	-	0.1	0.01	0.003	0.05	BIS (2012)
	Permissible Limit	1.0	0.2	NR	1.5	-	0.3	NR	NR	NR	

Table 4: Statistics of springs and Water Scarcity (WS) data in Uttarakhand.

State		**Uttarakhand**	**Source**
Water Consumption (lpcpd)	Maximum	65	Sundriyal and Rana (2022)
	Minimum	20	
	Average	35	
Distance to water source (M)		500	
Major Cause of WS		Mismanagement in water supply; Source dried or turned seasonal; Distance of source; Population growth; Deforestation and developmental (Anthropogenic) activities; Natural hazards	
Expected Consequence of WS		Impact on livelihood of people associated with agriculture and animal husbandry; Burden on women; More expenditure in terms of money and time in fetching water; Increase in local conflicts; Health issues.	
Suggested Solution of WS		Investment in water infrastructure such as construction of tanks of required capacity; Conservation and harvesting of rainwater; Plantation of oak trees in the catchment	
Total Number of Villages		16793	Gupta and Kulkarni (2018)
Total Number of Villages with Springs		594	
Percentage of villages which report having springs (%)		3.5	

Abbreviation used: lpcpd- liter per capita per day, WS- Water Scarcity, M- Meter

Table 5: Schemes across district under Uttarakhand Jal Sansthan with decrease in discharge in last three years (UJS, 2024).

District	50 to 75%	75 to 90%	Above 90%	Total
Dehradun	6	4	2	12
Pauri	26	120	39	185
Chamoli	15	9	-	24
Rudraprayag	12	-	3	15
Uttarkashi	10	2	1	13
Tehri	22	47	20	89
Almora	11	25	10	46
Champawat	7	35	12	54
Bageshwar	3	3	-	6
Nainital	18	7	-	25
Pithoragarh	9	16	6	31
Total	**139**	**268**	**93**	**500**

Table 6: Roles and Responsibilities of Organizations Involved in Water Resource Management and Conservation.

Sr. No.	Name of Organization	Name of Institution	Roles and Responsibility
1.	Government	Central Ground Water Board	Monitoring and managing groundwater resources
		Uttarakhand Jal Sansthan	Managing and Testing of water supply and sanitation services in Uttarakhand.
		Uttarakhand Irrigation Department	Developing and maintaining irrigation infrastructure.
		Wadia Institute of Himalayan Geology	Developing strategies for the conservation and sustainable management of spring water resources.
2.	Non-Government Organization	People's Science Institute	Conducting research and community-based projects on water harvesting.
		Himmotthan Society	Promoting sustainable water management and livelihood projects.
		Himalayan Environmental Studies and Conservation Organization (HESCO)	Implementing eco-friendly water conservation projects.
		Central Himalayan Rural Action Group (CHIRAG)	Working on water conservation and rural development projects.
		Central Himalayan Environment Association (CHEA)	Promoting environmental conservation and sustainable development in the Himalayan region.
		Self Help Groups (SHGs)	Promoting community engagement and sustainable practices, also promoting women's empowerment and socio-economic development and facilitate better management of water resources.
3.	Scientific Organization	Indian Institute of Technology, Roorkee	Developing innovative water harvesting technologies and providing technical and financial support.
		Advances Centre for Water Resources Development and Management	Contributed as a knowledge partner in most initiatives by providing scientific and technical knowledge and conducting training.

Table 7: Techniques and analytic parameters used in water quality testing.

Water characteristics	Name of Parameters	Instrument Name
Nutrients	pH	pH meter, pH paper/strips
	Turbidity	Turbidity meter, Nephelometer
	Total Dissolved Solids (TDS)	TDS meter, Gravimetric analysis
	Electrical Conductivity	Conductivity meter
	Alkalinity	Titration Method using sulfuric acid
	Calcium and Magnesium	Flame photometer and Titration method using EDTA
	Salinity	Refractometer, Conductivity meter, Drop Titration
	Fluoride, chloride, Sulphate and nitrate	Spectrophotometer, Color Comparator
	Total Hardness	Titration method using EDTA
Air	Dissolved Oxygen (DO)	DO Meter, Drop Titration
	Biochemical Oxygen Demand (BOD)	BOD Analyzer, Incubator
Heavy Metals	Total Iron, Barium,	Spectrophotometer, Color Comparator
	Aluminum, Copper, cobalt, Manganese, Lead, Cadmium, Chromium, Zinc	Atomic Absorption Spectrophotometry, Color Comparator
Biological	Bacteria, Coliform, *E. coli, Salmonella, Vibrio, Citrobacter, Shigella*	Most Probable number (MPN) method, Membrane Filtration Method, Enzyme-Linked Immunosorbent Assay (ELISA), Multiple tube fermentation method, Agar plate method

Table 8: Tools and Techniques of remote sensing (RS) and geographical information system (GIS) used in springs mapping, analysis and decision making

Category	Tools/ Software	Techniques	Purpose	Reference
Geospatial Analysis	ArcGIS, QGIS, Google Earth Pro	Mapping and delineating springsheds	Identifying recharge areas and catchments	Thakur *et al.* (2022)
Satellite Imagery	Landsat, Sentinel-2	Analyzing land use/land cover (LULC) changes	Understanding vegetation and land use impact on spring	Dhakal *et al.* (2022)
Topographic Analysis	Digital Elevation Models (SRTM, ASTER)	Generating slope, aspect, and elevation maps	Evaluating terrain characteristics influencing water flow	Dalponte *et al.* (2024)
Change Detection	Earth Resources Data Analysis System (ERDAS) Imagine	Multi-temporal satellite image analysis	Monitoring changes in recharge zones and spring health	Moisa *et al.* (20230

Fig. 1. Traditional water harvesting systems in Uttarakhand (a) Dhara, (b) Ufalda Dhara (c) Khal Dugout for Storing Water.
Source: https://connectingheritage.com/articleandnews/articles/uttarakhand

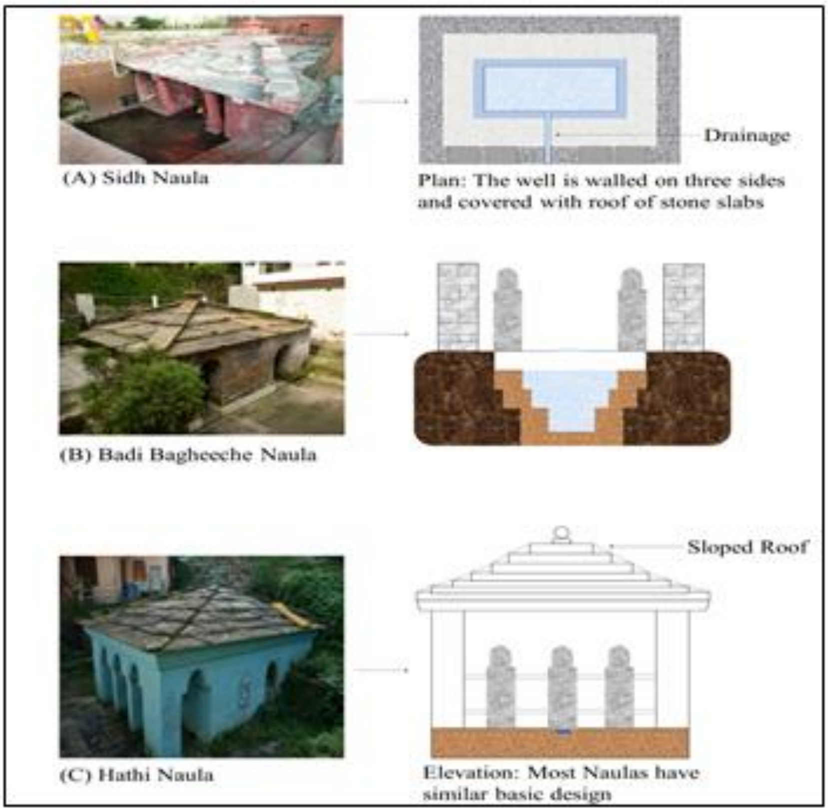

Fig. 2. Basic layout and components of different Naulas found in Uttarakhand Himalaya.
Image source: A, B and C: Bhandari and Kaur, 2023.

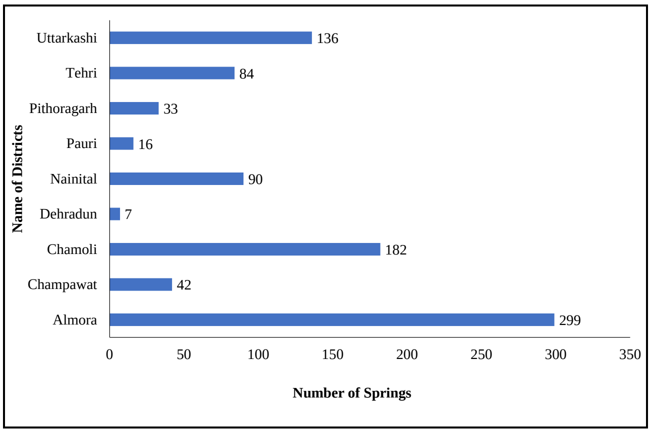

Fig. 3. Drying of springs across the districts (National Water Mission, 2018)

CONCLUSIONS

Traditional water harvesting systems hold immense cultural, environmental, and practical significance. They have supported communities for centuries by providing a sustainable source of water. However, due to changing climatic conditions and other socio-economic factors, their existence is at risk. The impact of climatic and environmental factors has significant reduction in water availability however, the conservation efforts by various organization including government bodies, NGOs, and local communities aims to preserve these systems. Women play a crucial role in maintaining and reviving traditional water sources, underscoring the importance of collective and gender-inclusive conservation practices. Protecting these traditional resources also contributed in maintenance of the rich heritage due to associated significant cultural beliefs as well as to ensure water security for future generations. Further, frequent monitoring of these resources is necessary to improve the water quality and health of local communities in the hilly states of Himalayan region where major population depends on the natural resource for their survival. Conservation and restoration of traditional water harvesting systems are associated with Sustainable Development Goals (SDG 6) with aim to ensure the availability and sustainable management of water and sanitation for all (UN, 2018). Sustainable management of water resources has significant contribution to other Sustainable Development Goals to achieve balance between the growing social, economic, and ecological needs of an increasing global population (Selvaraj *et al.*, 2022). Promoting sustainable water management, enhancing food security, and improving community resilience against climate change, thereby ensuring equitable access to water resources for future generations (Dube *et al.*, 2013).

Acknowledgement. The authors are thankful to the Director, School of Earth & Environmental Science and Vice-chancellor, Uttarakhand Open University for their support and encouragement.
Conflict of Interest. None.

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How to cite this article: Rohendra Singh, H.C. Joshi, Khashti Dasila, Neha Tiwari, Deepti Negi and Prashant Singh (2025). Cultural Significance and Conservation Challenges of Traditional Water Harvesting Systems of Uttarakhand Himalaya: A Critical Review. *Biological Forum, 17*(5): 111-123.