Title of Project: **Hydro-geological assessment and socio-economic implications of depleting water resources in tourist towns of Uttarakhand**

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HYDRO-GEOLOGICAL ASSESSMENT AND SOCIO-ECONOMIC IMPLICATIONS OF DEPLETING WATER RESOURCES IN TOURIST TOWNS OF UTTARAKHAND

(Final Report, December 2019 - March 2024)

Funded by

Ministry of Jal Shakti, National Water Mission, Department of Water Resources, (RD) and (GR), Government of India

Submitted by

Centre for Ecology Development and Research (CEDAR)

Partner Organization

Forest Research Institute
Deemed to be University, Dehradun
वन अनुसंधान संस्थान (सम विश्वविद्यालय)
(Academic Portal of Forest Research Institute, Dehradun)

CEDAR
CENTRE FOR ECOLOGY DEVELOPMENT AND RESEARCH

This study is in line with the Goal 1, 2 & 3 outlined by the National Water Mission of the Government of India
&
Sustainable Development Goal 6 & 13 established by the United Nations.

Goal 1: Comprehensive water data base in public domain.

Goal 2: Assessment of the impact of climate change on water resources.

Goal 3: Promotion of citizen and state actions for water conservation, augmentation and preservation, and Focused attention to vulnerable areas including over-exploited areas.

SDG 6: Clean Water & Sanitation

SDG 13: Climate change

Contents

List of acronyms and abbreviations

ADB	**Asian Development bank**
AWS	**Automatic Weather Station**
DDWS	**Department of Drinking Water & Sanitation**
DO	**Dissolved Oxygen**
DMO	**District Magistrate Office**
DPR	**Detailed Project Report**
ESs	**Ecosystem Services**
GIS	**Geographic Information System**
GCP	**Ground Coordinate Points**
GLM	**General Lake Model**
GoU	**Government of Uttarakhand**
IHR	**Indian Himalayan Region**
IITR	**Indian Institute of Technology Roorkee**
IPCC	**Intergovernmental Panel on Climate Change**
LDA	**Lake Development Authority**
LISS	**Linear Imaging Self-Scanning Sensor**
LiDAR	**Light Detection and Ranging**
LULC	**Land Use Land Cover**
MCM	**Million Cubic Meter**
MBT	**Main Boundary Thrust**
MLD	**Million Litre Per Day**
NGO	**Non-Government Organization**
NNPP	**Nainital Nagar Palika Parishad**
NRSC	**National Remote Sensing Centre**
NWM	**National Water Mission**
PBIAS	**Percent Bias**
PWD	**Public Works Department**
RMSE	**Root Mean Square Error**
RWH	**Rain Water Harvesting**
TSI	**Trophic Status Index**
ULBs	**Urban Local Bodies**
UJS	**Uttarakhand Jal Sansthan**
UPJN	**Uttarakhand Pey Jal Nigam**
WVI	**Water Vulnerability Index**
WSS	**Water Supply and Sanitation**

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Summary

This report presents the culmination of extensive interdisciplinary research carried out from December 2019 to March 2024, conducted by Centre for Ecology Development and Research (CEDAR) in collaboration of Indian Institute of Technology, Roorkee (IITR) and Forest Research Institute, (FRI) Dehradun, under the project **"Hydro-Geological Assessment and Socio-Economic Implications of Depleting Water Resources in Nainital".** The project was funded by Ministry of Jal Shakti, Department of Water Resources, RD and GR, Government of India.

The report presents a comprehensive assessment of Naini Lake's hydro-geological dynamics, focusing on water balance, trophic state, and isotopic analysis, alongside the development of a hydro-dynamic model for the lake system. It delves into the nature of local community's dependence on hydrological flows and ecosystem services, aiming to develop a deeper understanding of critical water zones essential for recharge. Through mapping critical water zones and conducting a water vulnerability assessment across different wards in Nainital, the report identifies areas of concern and potential interventions. Additionally, it outlines citizen science initiatives involving schools, colleges, and citizen groups to foster community engagement and awareness in their natural surroundings. The report emphasizes the importance of coordination between educational institutions, research organizations, citizen groups, and policymakers to develop effective networks around water supply and policy. Lastly, it seeks to influence policy at the local, state, and national levels by promoting "Catch the Rain" initiative. The main findings of the study are as follows -

1. Field monitoring network was established to monitor meteorological and lake water quality parameters. An Automated Weather Station was installed for high-frequency measurement of meteorological parameters. A standalone floating lake buoy was installed in the lake for high-frequency continuous monitoring of water quality parameters (T, DO, pH, EC, turbidity). Weekly water profiling (temperature, dissolved oxygen, electrical conductivity) was done using sonde equipment and transparency monitoring was done using secchi disk.
2. From the analysis of the lake water profile, we observed that in summer the lake is thermally mixed with slight to negligible thermal gradients and due to aeration in the lake the lake remains in a degassed state for most part of the year.
3. Despite a thermally mixed system, DO profiles revealed distinct hypoxic conditions in the bottom 5 m of the lake from June to August, especially in the northern sub-basin of the lake. Whereas the southern sub-basin depicts an intermittent emergence of hypoxic conditions between June and August. It shows the artificial aeration in the lake is not completely effective in avoiding the development of hypoxic state, particularly during summer months in the northern sub-basin. Prolonged hypoxia in lake bottom may adversely affect the ecosystem dynamics and fish habitats.
4. From the analysis of Secchi disk data, Nainital Lake was found to be in Eutrophic state over the study period.
5. A one-dimensional hydrodynamic model, General Lake Model (GLM) was developed for Nainital Lake using the observed datasets from the monitoring network. The model was calibrated and validated for lake water levels, continuous profiles of temperature at daily time steps. The model simulations were used to compute lake water balance components.
6. The findings underscore the heavy reliance of community on Naini Lake for household consumption (55%) and commercial ventures (41.67%), underscoring its indispensable role in both economic and domestic realms. While a small percentage of respondents (3.33%) do not depend on Naini Lake, suggesting potential alternative water sources (springs).

7. During the multi-risk assessment, a broad spectrum of stakeholders prioritized socio-economic risks, followed by natural risks, regulatory risks, and environmental risks. This trend could be attributed to the timing of the survey, which took place shortly after the lockdown period.
8. In Key Informant Interviews (KIIs) and Focus Group Discussions (FGDs) with stakeholders, it emerged that irregular water supply is not the sole issue concerning the water challenges in Nainital. Institutional overlapping emerged as a significant problem affecting water governance in the city, resulting in accountability gaps.
9. The study identified 13 recharge zones and 9 springs within the area. Through the identification and geotagging of these springs and critical water zones, alongside acknowledging the importance of Nainital's drainage system, we gain insight into the availability of freshwater resources.
10. Regarding water resources, the study identified three primary sources of drinking water in Nainital city: Naini Lake (through lake bank filtration), Sukhatal (through groundwater abstraction), and springs. Analysis revealed that 76% of the total water supply is sourced from Naini Lake, 22% sourced from Sukhatal through groundwater pumping, and the remaining 2% is sourced from springs.
11. Concerning water distribution, it was examined that the current infrastructure comprises 15 tubewells, with 11 situated lakeside and 4 located on the lake-bed of Sukhatal. These tubewells collectively yield 8.0 million liters per day (mld) of water, while the remaining 0.167 mld is sourced from springs. Additionally, there are four water pump houses managing water distribution across twenty designated water supply zones throughout the city.
12. Study indicates that 4 out of 15 municipal wards of the town fall under the category, 'highly vulnerable zone' as far as exposure, sensitivity and adaptability towards water changing climatic scenario is concerned.
13. As part of the citizen-led initiatives within the study, two Automated Weather Stations (AWS) were installed in the town. The primary agenda behind this initiative is to empower citizens and communities to play an active role in collecting vital environmental data. With the same intent, CEDAR team also compiled a book titled "Bird Diversity of Naini Lake Catchment" to assess the environmental health of the lake and its surrounding area by focusing on the presence of birds. The important thing about this initiative is that all the data and information presented in this book was collected with the assistance of citizen scientists, bird watchers, and photographers from Nainital.
14. To establish a platform aimed at improving access to water-related information in Nainital, we have launched the website www.nainitalwater.com. This comprehensive online resource provides unrestricted access to a wide range of information regarding Nainital's water dynamics.
15. In an effort to encourage responsible water usage, a preliminary study on exploring the Potential of Rainwater Harvesting Structures in Nainital was conducted. The findings revealed significant potential for implementing Rainwater Harvesting (RWH) in Nainital. These results were further translated through a popular article published on the India Water Portal.
16. In order to engage policy influencers, a comprehensive policy brief was crafted. This document highlighted "Catch the Rain" campaign initiated by the Government of India and assessed the feasibility of implementing sustainable water management practices in four cities: Nainital, Haldwani, Dehradun, and Mussoorie, by promoting Rainwater Harvesting (RWH) techniques.
17. Study aimed to share the research findings with diverse audiences, ranging from the scientific community to the general public. During the study multiple forms of communication were developed including research papers, popular articles, policy briefs, video documentaries, infographics, books, display materials, and a website to spread awareness about the hydrological dynamics of Nainital.
18. The purpose of the study was to share the research findings with a variety of audiences ranging from the scientific community to the general public. Several forms of communication were developed

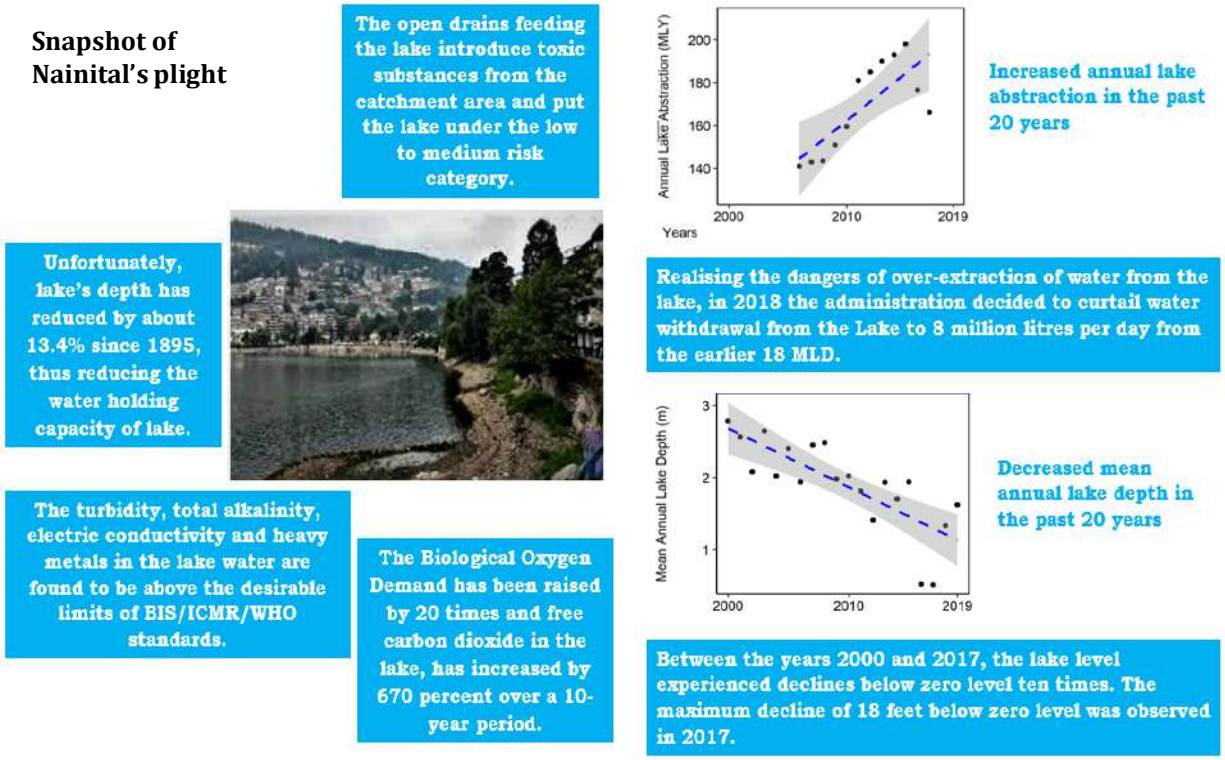
during the study, including research papers, popular articles, policy briefs, video documentaries, infographics, books, display materials and a website to spread awareness about the hydrological dynamics of Nainital.

Research context

Urban agglomerations across the Indian Himalaya are undergoing rapid expansion and economic transformation. Ever-growing water shortages are a direct and dangerous consequence of such unplanned expansion. When it comes to water, the majority of towns and cities in Indian Himalayan Region (IHR) are functioning beyond their carrying capacity. While their size has grown manifold in the past few decades, most remain dependent on springs, streams and local lakes to meet their water requirements. Most of these water sources have depleted due to degradation of their catchment areas. Water insecurity in the region is further exacerbated by the effects of climate change. Some of the larger towns have been drawing water from distant rivers or large springs, but here they too face water scarcities.

Sustainability of water supply in hill towns is a function of both resource sustainability and the quantum of demand. This is controlled by a number of factors like - duration of rainfall, residence time of snowpacks, forest degradation, change in land use and critical water zones and geology of the area. Skewed seasonal availability and increasing water demand impose severe strains on the water supply systems of the hill towns. Currently, in most of the hill cities, this imbalance is dealt with by lowering the water supply pressure, the duration of piped water supply, and rationing.

In this context, the case of Nainital city (a tourist destination in Uttarakhand state) is particularly significant. On one hand the city is facing the negative impacts of climate change and unplanned urbanization, while on the other side it is badly affected by the problem of water shortage during the summer season.



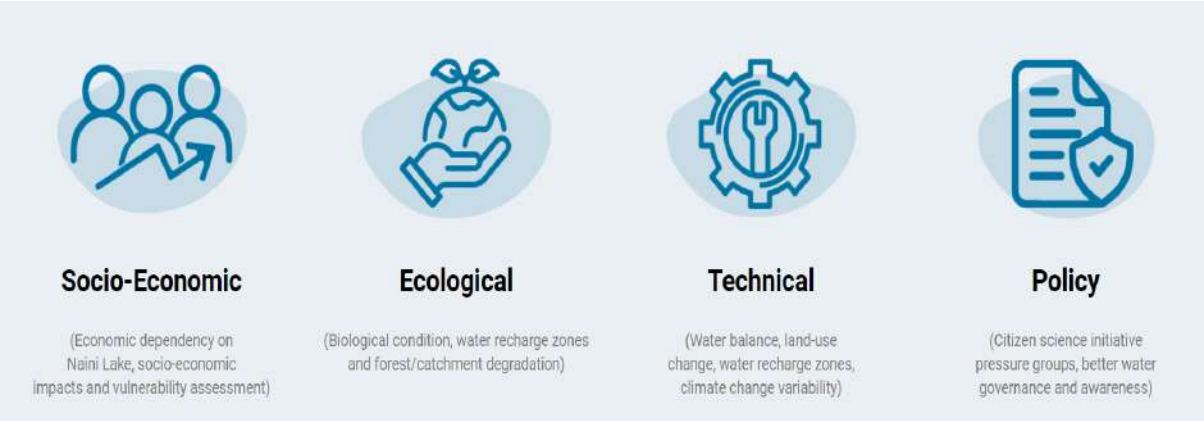
Emerging water issues in Nainital

The overall environmental degradation of Nainital is a result of unsustainable development driven by sectoral and departmental approach with little focus towards the natural ecosystem, geological character and associated environmental fragility of the town. Visible impacts of environmental degradation had started unravelling itself by consistent decline in the lake levels in the 21st century. Between 2000 and 2017 the lake level experienced declines below zero level ten times. The maximum decline of 18 feet below zero level was observed in 2017. After this incident, the recurring lake level decline caught the attention of the concerned citizens of Nainital, scientists, policy makers, Non- Government Organisations (NGO) and media.

About the project

The project **"Hydro-Geological Assessment and Socio-Economic Implications of Depleting Water Resources in Nainital"**, was commissioned to Centre for Ecology Development and Research (CEDAR) by Ministry of Jal Shakti, Department of Water Resources, RD and GR in partnership with Indian Institute of Technology, Roorkee (IITR) and Forest Research Institute, (FRI) Dehradun. Study was committed to focus on devising citizen science initiatives on long term monitoring, collecting data and compiling long term records which will reflect trends and changes, assessing the hydrological balance of the lake and water vulnerability of stakeholders within the municipal confines of Nainital.

Major components of the study



Four major components of the study

Approach

Apart from collecting primary data, this research involves a process of engagement with various stakeholders. From helping to engage and strengthen civic groups, collaborating with research institutions, helping to convince decision makers in government, political and civic leadership, the process followed is inclusive and common across all levels and focuses on building a sense of consent and ownership. With respect to research and goal-setting, emphasis is placed on 'knowledge co-production', 'translational ecology' and joint consideration of socio-ecological and political contexts to improve environmental decision-making. Three categories of research are applied – basic, applied and user driven – with respect to research processes and the types of decisions to be made.

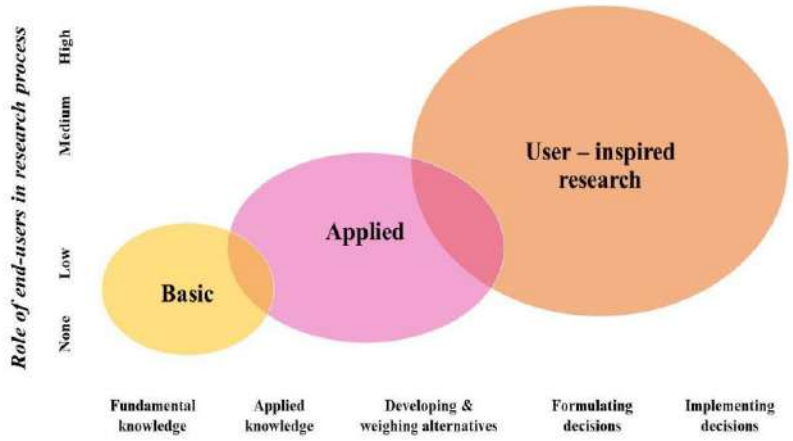


Fig. 1: Illustrative representation of the approach used in study.

Objectives

Entire study was divided into nine objectives. Table 1 provides a breakdown of the objectives being pursued by responsible institutions.

Table 1: Objectives of the study.

No.	Objectives	Responsible institution
1.	Hydro-geological/dynamic assessment of Naini Lake w.r.t Water balance, trophic state, isotopic analysis in conjunction with water balance.	**IITR**
2.	To develop a hydro-dynamic model for the lake system.	**IITR**
3.	To explore the nature of dependence of local communities on hydrological flows and other ecosystem services.	**CEDAR**
4.	To develop a deeper understanding of critical water zones and help identify areas critical to water recharge.	**CEDAR**
5.	Mapping of critical water zones.	**CEDAR**
6.	Water Vulnerability Assessment of different wards in Nainital.	**FRI**
7.	To develop citizen science initiatives through schools, colleges and citizen groups and catalyse such groups to influence good water policy.	**CEDAR**
8.	To coordinate between schools, colleges, research institutions, citizen groups, and the district administration and policy–makers, in order to help develop effective networks around water supply and policy.	**CEDAR**
9.	Influence Policy at Local, State and National level.	**CEDAR**

Study site

About Nainital

Nainital is one of the most popular tourist attractions in the Indian Himalayan region. It is perched between 29°24' N latitude and 79°29' E longitude in proximity to the Main Boundary Thrust (MBT) that separates the Shiwalik from the Lesser Himalaya. The Nainital Hills of the Kumaon Himalaya is structurally one of the most disturbed belts of the Himalayas. Nainital is situated on an east-west running valley bound on the north by China peak (2611.5m) continued by Alma peak and the Sher ka Danda to the east where the ridge descends to the level of the lake. On the west is the hill of Deopatha (2435m) and on the south Ayarpatha hill is placed with an elevation of 2274.1 meters. The hilly terrain of Nainital is in close proximity of a major regional tectonic discontinuity of the Himalayan orogen; the main boundary Thrust (MBT). This tectonic boundary is recognised as being seismically active which makes it highly vulnerable.

About Naini lake

The kidney bean shaped Naini Lake is the most prominent feature of the town. The presence of 100 m wide ridge in the middle divides the lake into two parts with different maximum depths. The lake has a special significance to the people living in the city, it provides life sustaining water and a huge proportion of the economy of the town depends upon the lake.

Fig. 2: Panoramic view of Naini lake

Lake is divided into two subbasins viz., Mallital and Tallital by a 100 m wide transverse underwater ridge, 7 m below surface. It has an outfall at the South Eastern end known as Ballia Nala. Lake is surrounded with Naina Peak to the North-West side, Tifin Top to the South-West side and Snow View Peak to the North.

Table 2: Important features of Naini lake

Nature	**Alkaline**	**Maximum depth**	**27.3 (m)**
Type	**Tectonic, warm monomictic**	**Mean depth**	**16.2 (m)**
Length	**1432 (m)**	**Catchment area**	**About 4.7 (sq. km)**
Surface area	**48 (ha)**	**Volume (in 2018)**	**81,08,393 (m^3)**

Methodology

Table 3 illustrates the conventional methodologies employed for key activities aimed at achieving the primary objectives outlined in the study.

Table 3: Methodology of key activities

S. N.	Key activities	Methodology
1.	**Water balance of Naini lake**	**Water balance equation (ΔS = Inflow – Outflow)** **In case of Lake Nainital, the inflow term includes surface inflow (Si), subsurface inflow (SSi), inflow through drains (Di) and direct precipitation (Pi). The outflow term includes controlled surface outflow through sluices and surface leakage through sluice gates (So), free water evaporation (Eo), subsurface outflow (SSo) and pumping by government agencies (Wo).**
2.	**Hydro dynamic analysis of the lake**	**Open-source modelling system** **Water systems Vs Atmospheric systems**
3.	**Assessment of ecosystem services provided by lake**	**Qualitative analysis through KII, FGD and household surveys**
4.	**Identification of water recharge areas and mapping of critical water zones**	**GIS modelling**
5.	**Water Vulnerability Assessment**	**WVI= f (exposure, sensitivity, adaptive capacity)**
6.	**Citizen science and Policy Assessment**	**Open access portal, Roof water harvesting, Community led data collection, Systematic policy review**

Objective wise findings

Objective 1: Hydro-geological/dynamic assessment of Naini lake

Key activities

1. **Consultations with Stakeholders.**
2. **Lake System Understanding using monitored field data by conducting contour plot analysis.**
3. **Trophic Status Index for Nainital lake.**

To start the project work for developing lake system understanding and to develop a hydrodynamic model for the lake, we adopted a systematic approach of conducting the site survey followed by consultation with stakeholders, manual lake sampling and subsequently lake and catchment instrumentation. The work started by conducting a site survey and consultation with stakeholders of the Nainital lake, the Irrigation Department and Lake Development Authority, Nainital in early 2021 with subsequent lake and catchment survey. With the aim of developing a thorough system understand, manual field sampling was started in late June 2022 followed by installation of instruments in and around the lake catchment for the research work. Vertical water profiling is being conducted in Nainital lake since 26th June 2021 with a YSI ProDSS Multiparameter Digital Water Quality Meter to measure the basic water quality parameters along with secchi depth monitoring. An Automated Weather Station (AWS) was setup in the lake catchment to monitor the meteorological parameters on 2nd February 2022. A LiDAR based stream gauging equipment system to measure the water level fluctuations in the

perennial stream - Naina Devi Drain was set up on 3rd March 2022. A real time water quality monitoring standalone station buoy was set up in the lake on 20th June 2022. The field monitored data has been utilized to develop the lake system understanding and set up (calibration and validation) of a 1-D lake hydrodynamic model called the General Lake Model (GLM). The details related to ppreliminary survey, field work and site selection is given in Annexure 1.

Consultation with stakeholders

The team visited Irrigation Department Nainital and the Lake Development Authority Nainital in early 2021 to meet with authorities. From the meetings, the different departments monitoring different aspects of the lake were identified. The drains flowing into the lake are maintained by the Irrigation Department. Daily rainfall data and lake level data are also collected by the department. On request of IIT Roorkee team, the rainfall and water level data are shared by the department with the team. The outflow from the lake through the 5 sluice gates was being controlled by the Public Works Department till 2017. The charge was then handed over to Irrigation department from 2018. Hence, currently the outflow from the lake is being regulated by the department. A summarised list of various offices working on different aspects of the lake are:

1. **Irrigation Department, Nainital:** Maintenance of drains flowing into lake, daily rainfall (non-recording type gauge), lake level data (staff gauge located at Southern end of lake) and outflow from the lake.
2. **Nagar Palika, Nainital:** In lake processes and maintenance.
3. **Nainital Lake Development Authority:** Aeration program running since 2007. Aerators are being operated for 18 hours per day as per the consultation with Lake Development Authority, turned off from 10:00 to 16:00 per day. During lockdown due to COVID-19 it was being operated from 10:00 to 16:00 or so, hours were not fixed. Discrete water quality sampling is being done from random locations as per the authorities.
4. **Jal Sansthan, Nainital:** Operates the tubewells for pumping water from the lake for the water supply to the town. 8 mld water is being pumped daily from the lake.

Lake system understanding using monitored field data by conducting contour plot analysis

A vertical profiling program was started in Nainital lake at a weekly frequency. Six sample points were selected in the lake longitudinally from north to south (S1, S2, S3, S4, S5 and S6). Sample point I is at the confluence of the Naina devi stream with the lake and sample point O is located near the outflow.
To understand the thermal structure of the lake, we have conducted a contour plot analysis for the lake. The lake water temperatures varied from 8°C to 24°C. From the isothermal plots in Figure 3, we observe that the lake is a thermally mixed system from November through February. A very weak thermal gradient is observed along depth in the summer months of June to September. The weak thermal gradient observed is different from the past studies (Gupta and Deshpande 2004). The past study showed a precisely defined thermocline and metalimnion for the lake. However, we observe a very small thermal gradient which is attributable to the aerators operating in the lake since 2007. Isothermal plots for all the field sample points (S1 to S6) in Figure 3 reveal that the observed patterns in the temperature profile are similar at all the lake monitoring stations for the study duration of (June 2021 to January 2024).

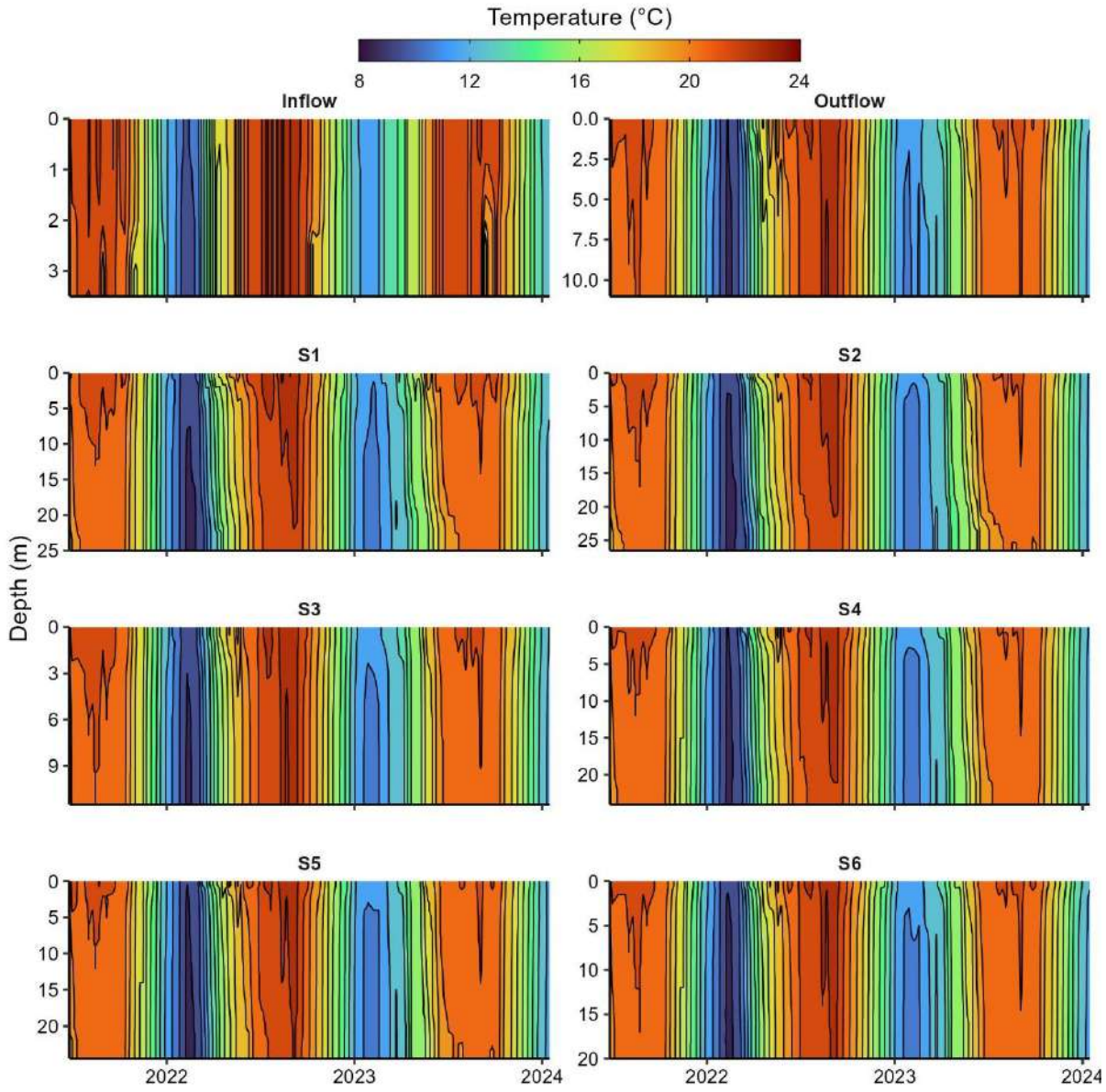


Fig. 3: Isothermal plots for lake Nainital at all sampling stations.

To develop an understanding of the lake dissolved oxygen conditions we developed a contour plot for the monitored dissolved oxygen at all the sampling locations. The lowest value of dissolved oxygen obtained in the lake was 0.21 mg/L in the hypolimnion on July 15, 2022. The highest value observed was 11.48 mg/L on February 24, 2022 in the epilimnion. The past study from NIH (Report 1999) states that the dissolved oxygen in the top 3 m zone varies from 18.4 mg/l (maximum) to 1.3 mg/l (minimum). and the DO level below 9 m in the lake is negligible. NIH report also states that, between June and January, DO was virtually absent and anoxic conditions prevailed in the bottom waters. In the current study, from Figure 4, we observe the development of hypoxic zone at lake bottom in isopleths of DO from June-August. A significant reduction of dissolved oxygen is observed from figure at the lake bottom in the peak summer months. An interesting observation is that the hypoxic zone in the northern basin is more prominent and persist for majority of the summer months at the bottom 5m of the hypolimnion. However, for the southern basin, hypoxic zone develops only in the early few months of summer season.

Distinct seasonal variations in DO are evident in the plot with higher concentration in the winters and low in the summers. In the present study as the hypoxic zone is present only for a period of 3 months in the bottom 5 m of the lake, the lake volume with negligible DO is very less than the previous NIH study (1999). Subsequently, when the mixing takes place in winters, the DO level of the lake does not drop drastically, and the DO level reaches its peak in winters as the temperatures are at lowest. The aeration program underway in the lake since 2007 (17 years) has significantly reduced the anoxic state of the lake. However, hypoxia is still observed in peak summer months (June-Aug) in northern basin and for short durations in southern basin.

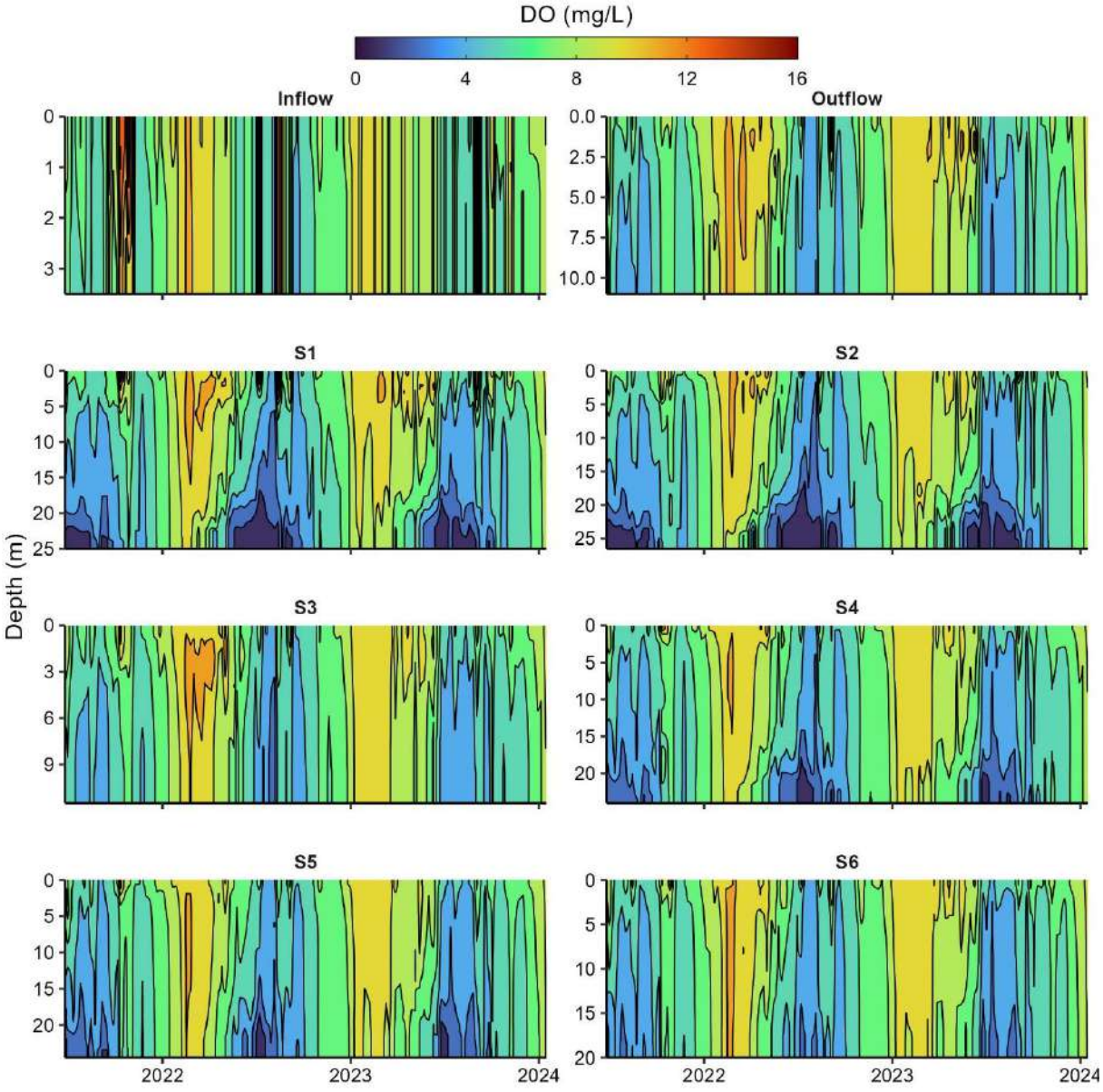


Fig. 4: Contour plots of dissolved oxygen (DO) for lake Nainital at all sampling stations.

Trophic Status Index for Nainital lake

Trophic Status Index (TSI) is a classification system utilized to classify lakes based on the biological productivity of the lake. The most frequently used Trophic Status Index is the Carlson's Trophic Status

Index which was proposed by Carlson in 1977 and is used by the United States Environmental Protection Agency (US EPA). The following equation have been given by Carlson (1977):

TSI (SD) = 60 – 14.41 ln (SD)

Where, SD = secchi depth.

The TSI Index of a water body ranges from 0 to 100 and according to Carlson and Simpson (1996) can be divided into the following trophic classes:

Trophic Status Index	Trophic class
<30 – 40	**Oligotrophic**
40 – 50	**Mesotrophic**
50 – 70	**Eutrophic**
70 – 100+	**Hypereutrophic**

Oligotrophic lakes have low productivity due to nutrient deficiency. Eutrophic lakes have high biological productivity due to excessive nutrient availability, specifically nitrogen and phosphorus. The waters are covered by aquatic plants or algae. A hypereutrophic lake is a nutrient dense highly productive waters characterized by frequent and severe algal blooms along with reduced transparency. Using the equation given by Carlson (1977), we computed the TSI based on secchi depth for lake Nainital for a period of 2.5 years from June 2021 to January 2024. From Figure 5 we observe that the lake can be classified as eutrophic (green zone) for most part of the study duration. The lake can be observed in the mesotrophic classification for a short period between August 2022 to January 2023. Monitoring the secchi disk transparency for a long duration gives an indirect insight into the biological activities which may be happening in the lake. A high frequency secchi disk monitoring is a quick, simple, cost effective and accurate method of determining the lake water quality.

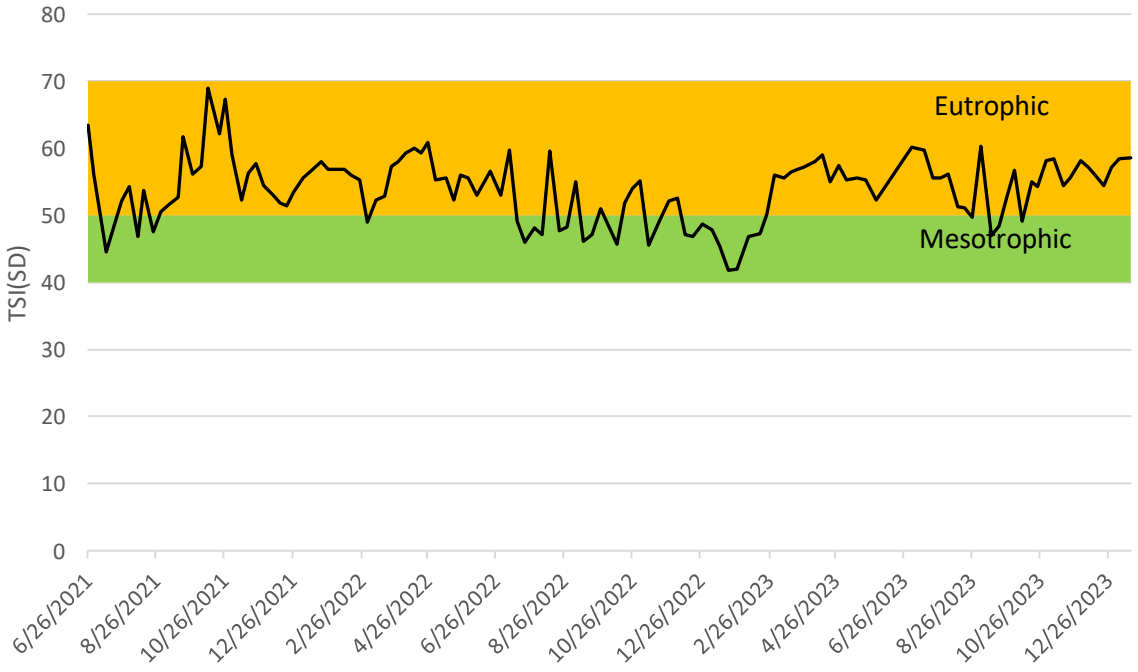


Fig. 5: Trophic status index computed from the monitored secchi disk data.

Objective 2: Development of a Hydrodynamic Model for the lake system

Key activities

1. **Model simulations.**
2. **Calibration**
3. **Validation**
4. **Water balance**
5. **Impact assessment**

The development of a hydrodynamic model for the Naini Lake system holds paramount importance for various reasons. Firstly, Naini Lake, situated in the picturesque town of Nainital, is not only a significant natural reservoir but also a crucial source of water for domestic, agricultural, and recreational purposes for the local populace and tourists alike. A hydrodynamic model would enable a comprehensive understanding of the lake's hydrological processes, including inflows, outflows, sedimentation rates, and water quality dynamics. This knowledge is indispensable for effective management and conservation efforts. Furthermore, in the face of climate change and increasing anthropogenic pressures, a robust hydrodynamic model serves as a valuable tool for devising sustainable strategies to safeguard the Naini Lake ecosystem's long-term health. Following activities were undertaken to achieve the objective.

Model simulations

- Calibration period: 04 Feb 2022 to 30 April 2023 at daily time step.
- Validation period: 01 May 2023 to 15 January 2024 at daily time step.

Model Results

Calibration

The GLM model has been calibrated for a period of 15 months from 04 February 2022 to 30 April 2023. Inputs included a time series of meteorological data, and lake-specific data including physiography (surface area, maximum depth, elevation, latitude, and longitude). The GLM model is calibrated for the lake water level by adjusting inflow factor and seepage rate (Figure 6). Since pumping stations withdraw water from the ground but not directly from the lake, withdrawal is accounted as seepage in the model. The calibrated parameter values of inflow factor are 0.35 and the seepage rate is 0.0175 m/day. To compute the goodness of fit of the model's predicted lake water level, we used the root mean square error (RMSE) and percent bias (PBIAS). The model performance measures were an RMSE of 0.3m and a PBIAS of 0.0028.

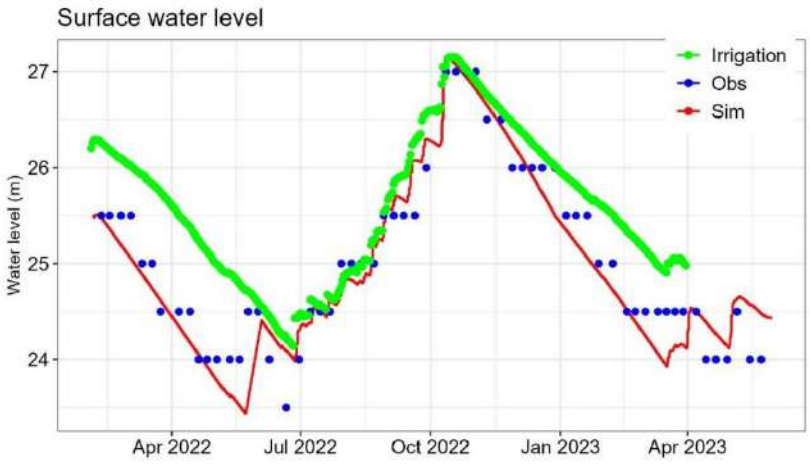


Fig. 6: Calibrated lake water levels by GLM lake model

Validation

The GLM model has been validated for a period of 9 months from 01 May 2023 to 15 January 2024 (Figure 7). To compute the goodness of fit and assess the model performance, we used the root mean square error (RMSE) and percent bias (PBIAS). We observed an RMSE of 0.35m and a PBIAS of -0.0019. The low RMSE value in the calibration and validation periods reveal that the model is performing satisfactorily in simulating the lake water levels. The model is further calibrated and validated for lake water temperature. The model can be used for estimating the lake water balance components.

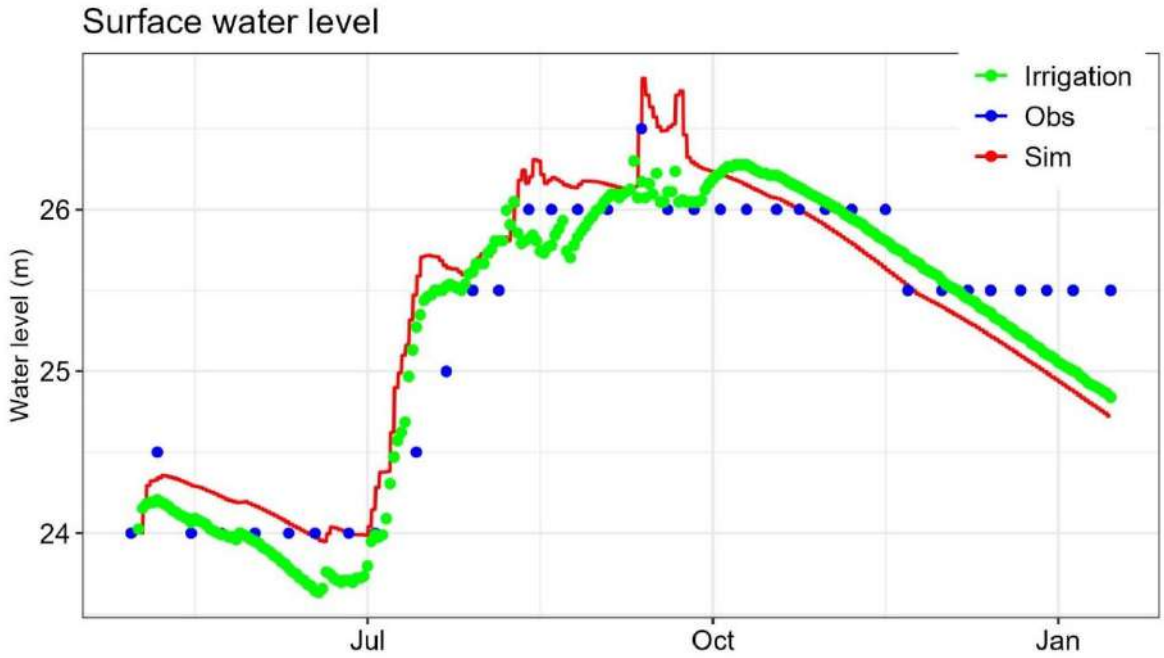


Fig. 7: Validated lake water levels by GLM lake model.

Water balance

GLM lake model is used to compute monthly water balance components of Nainital Lake. In the model, inflows to the lake system include surface water inflows and groundwater inflow. Outflows consists of lake outflow through sluices and seepage losses. Table 4 list the monthly estimates of water balance components for Nainital Lake from February 2022 to December 2023. The mean lake storage in this period is 7.11 MCM that drop to a range of 6.56–6.86 MCM in pre monsoon season and rise to the range of 7.3–7.96 MCM by the end of monsoon season. The inflow to the lake fluctuates substantially as denoted by the mean monthly value of 0.23 MCM with the standard deviation (SD) of 0.24 MCM. The inflows to the system are largely controlled by the rainfall that shows high seasonal variation. It potentially causes the large variability in the inflows. On the other hand, the outflows from the system are relatively consistent with the mean value of 0.29 MCM and SD of 0.08 MCM. It is because a large fraction of outflows is the constant rate of seepage losses in GLM model for the lake. The mean monthly estimate of direct rainfall contribution to lake storage is approximately 0.04 MCM with SD of 0.09 MCM. The rainfall is mainly experienced in monsoon and winter months while other months are mostly dry. The lake water level also experienced considerable fluctuations that peaks to 26.8 m by the end of monsoon months, whereas drops to 23.7 m before the onset of monsoon. The mean monthly water level

is 24.91 m with SD of 0.8 m. During the modelling period, i.e., February 2022 to December 2023, the lake storage experienced a reduction of 0.02 MCM. It resulted in a net reduction of lake level from 0.4 m by the end of study period.

Table 4: Water Balance of Lake Nainital computed using developed GLM lake model.

Year	Month	Volume	Change in Storage	Inflow	Outflow	Rain	Level
		(MCM)	(MCM)	(MCM)	(MCM)	(MCM)	(m)
2022	2	7.30	-0.18	0.04	0.22	0.01	25.3
2022	3	7.05	-0.28	0.00	0.29	0.00	24.8
2022	4	6.77	-0.27	0.00	0.27	0.00	24.1
2022	5	6.56	0.16	0.03	0.28	0.37	23.7
2022	6	6.79	0.08	0.15	0.27	0.21	24.2
2022	7	6.93	0.21	0.41	0.28	0.07	24.5
2022	8	7.15	0.34	0.58	0.29	0.07	25.0
2022	9	7.54	0.31	0.51	0.28	0.09	25.9
2022	10	7.96	0.25	0.76	0.47	0.10	26.8
2022	11	7.83	-0.30	0.10	0.39	0.00	26.5
2022	12	7.51	-0.34	0.05	0.39	0.00	25.8
2023	1	7.21	-0.26	0.02	0.29	0.01	25.1
2023	2	6.95	-0.25	0.01	0.26	0.00	24.6
2023	3	6.76	0.02	0.17	0.28	0.04	24.1
2023	4	6.86	-0.03	0.24	0.27	0.04	24.3
2023	5	6.83	-0.01	0.30	0.22	0.00	24.3
2023	6	6.70	-0.14	0.07	0.22	0.00	24.0
2023	7	6.88	0.32	0.55	0.23	0.01	24.4
2023	8	7.21	0.34	0.56	0.23	0.01	25.1
2023	9	7.32	0.01	0.49	0.49	0.00	25.4
2023	10	7.29	-0.06	0.17	0.23	0.00	25.3
2023	11	7.19	-0.14	0.08	0.22	0.00	25.1
2023	12	7.01	-0.20	0.03	0.23	0.00	24.7

Impact assessment

Changes in monsoon rainfall can lead to a fluctuation in the lake water levels and lake storage. Lowering of water levels can adversely affect the water supplies as the lake and other services provided by the lake. It can also affect the aquatic ecosystem in the lake. Historical observation and future climate projections reveals a significant change in rainfall patterns in the north Himalayan region. Accordingly, we evaluate the potential impact of change in rainfall on the lake water levels using GLM model developed to the lake. Since, majority of total annual rainfall is received during monsoon months, we considered four scenarios of change in monsoon rainfall as follows:

(a) – 20%; (b) + 20%; (c) – 50%; and (d) + 50% change in monsoon rainfall

The lake water balance components are simulated using calibrated GLM model for the selected rainfall change scenarios. Figure 19 shows the total change and the percent change in the total volume of the lake. For a ±20% change in monsoon rainfall, the total volume of the lake changed by +2.33% and -2.5%, respectively. For a ±50% change in the monsoon rainfall, we observed that the total volume changed by +3.11% and -3.54%, respectively (figure 8).

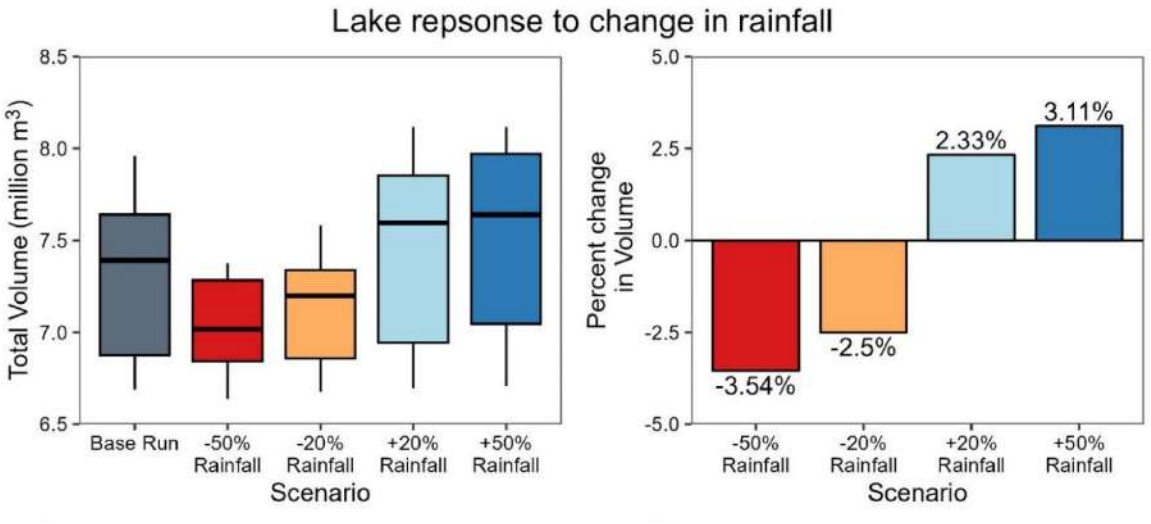


Fig. 8: Lake response to change in monsoon rainfall.

Objective 3: To explore the nature of dependence of local communities on hydrological flows and other ecosystem services.

Key activities

1. **Identification of key stakeholders and institutions involved in water management in Nainital.**
2. **Hydrological flows of Naini lake.**
3. **Listing of Ecosystem Services (ESs) provided by lake and its catchment.**
4. **Community's dependency on lake.**
5. **Risk assessment and its prioritization.**
6. **Consequences of anthropogenic activities on hydrological dynamics of Nainital.**

The Naini Lake ecosystem is a complex network of interconnected elements, revealing the complex relationships between stakeholders, hydrological flows, and the essential ecosystem services (ESs) it provides. This ecosystem serves as a critical source of sustenance for both the local communities and the diverse flora and fauna that thrive in its surroundings. The delicate balance of hydrological flows, including precipitation, runoff, and groundwater recharge, plays an important role in shaping the lake's ecosystem dynamics. Stakeholders, ranging from the residents to institutions, are essential components influencing the lake's health and resilience. The symbiotic relationship between these stakeholders, hydrological processes, and ecosystem services underscores the necessity of sustainable management. By unveiling these vital connections, we gain a deeper appreciation for the Naini Lake ecosystem and recognize the importance of preserving its harmony for the well-being of both nature and society.

To achieve this objective, an effort has been made to understand this framework by employing stakeholder analysis and examining the institutional framework. Additionally, the exploration extends to understanding the hydrological flow and ecosystem services (ESs) of Naini Lake, identifying water inflow and outflow balance and ESs, and assessing the reliance of stakeholders on the lake by prioritizing ESs. The chapter also states the risks acknowledged by stakeholders and investigates the repercussions of human-induced activities that make impact on the ecological integrity of the lake.

Institutional arrangement

Identification of key stakeholders: The identification of key stakeholders for Naini Lake involved a thorough assessment of their respective roles, responsibilities, and usage patterns towards the lake. This comprehensive analysis broadly considered the multifaceted dimensions of stakeholder's involvement and their dependency/influence over the lake. After brainstorming, the possible stakeholders of Naini lake are listed in the following table.

Table 5: List of possible stakeholders of Naini lake

S. No.	Name of Stakeholder	Directly related	Beneficiaries
1	**Citizens of Nainital**		√
2	**Jal Sansthan**	√	
3	**Municipality**	√	
4	**Irrigation Department**	√	
5	**Lake Development Authority (LDA)**	√	
6	**District Magistrate Office (DMO)**	√	
7	**Educational Institutes (University, Training Institute, Schools)**		√
8	**Community of Scientists and Ecologists**		√
9	**Tourists**		√
10	**Taxi owners, Horsemen, Rickshaw pullers, Boatmen**		√
12	**Trade Association (Shop owners, Petty Traders, Vendors)**		√
13	**Hospitality industry (Hotel, Restaurants)**		√
14	**Low income Group**		√
15	**Local Non-government Organizations, Civil societies**		√

Institutions involved in water management in Nainital: The water supply of Nainital is operated and maintained by Uttarakhand Jal Sansthan (UJS), working under Department of Drinking Water & Sanitation (DDWS), Government of Uttarakhand (GoU). UJS undertakes small budget capital works and is responsible for planning, survey, DPR (Detailed Project Report) preparation and execution of water supply and sewerage projects. Large capital works and overall planning are carried out by another corporation Uttarakhand Pey Jal Nigam (UPJN), also comes under DDWS. Although it is supposed to be a municipal function, Nainital Nagar Palika Parishad (NNPP) is not involved in the planning, design, construction, operation, maintenance, and service delivery of this important urban infrastructure. This section deals with the analysis of current situation of water supply, its problems, key issues and the likely scenario of water supply with respect to water demand, resources, system requirements and related aspects.

There are some other departments and agencies that are not directly or significantly involved in the Water Supply & Sanitation (WSS) sector but nevertheless play an important oversight, regulatory or financing role. In Nainital, Irrigation Department played an important role in the lake related matters. The maintenance responsibility of lake was handed over to the Irrigation Department from Public Works Department (PWD). Outflow from lake through 5 sluice gates controlled by PWD department till 2017 but charge handed over to Irrigation Department since 2018. Another authority plays important role in related to lake water is, Nainital Lake Region Special Area Development Authority (NLRSDA). It implements the restoration works and has the power to be restrict in permitting constructions to take place in and around the lake, which is clearly part of the catchment.

There are other agencies, which depending upon their geographical jurisdiction, also involved in the delivery of WSS (Water Supply and Sanitation) services. Some, like Urban Local Bodies (ULBs) and SWAJAL may be directly involved in the implementation or management of drinking water supply and sanitation schemes, while some others like Social Welfare, Forest Department and Asian Development Bank (ADB) either provide specific support/funds or provide clearances for specific schemes and projects. Refer table -6 for detailed information related to roles and responsibilities of the institutions responsible for the water management in Nainital.

Table 6: Roles and responsibilities of different institutions for water management in Nainital

	Institutions	Roles and responsibilities
1.	**Water Management Authority**	UJS- Water conservation measures, policy, laws, and tariff (in consultation with District Administration); use of efficient appliances; scheduling of water supply; public awareness; separating the rainwater from the sewer line of the houses located in the city and connecting it to the main drains etc. UJN – Construction and maintenance of tertiary level sewage treatment plants and disposal of the treatment effluent into the drains.
2.	**Nainital Nagar Palika Parishad (NNPP)**	Cleaning of lake; solid waste management; proper provision and management of public facilities; complete ban on disposal of domestic waste in drains and arrangement of its disposal.
3.	**Irrigation Department**	Work related to constructions and maintenance of 62 drains leading to Naini lake, Sukhatal and the regulating structure; lake water quality monitoring and display of water level; formulation of guidelines for outlet gate operation; disconnecting rainwater drains from sewers.
4.	**Nainital Lake Region Special Area Development Authority (NLRSDA)**	Check on unauthorized construction and prevention of disposal of construction debris into drains.
5.	**Forest Department**	Notification of wetland; Rain Water Harvesting plan in the catchment; catchment area treatment; checking soil erosion in the catchment.
6.	**Public Works Department (PWD)**	Work related to operation, maintenance and cleaning of road side drains and related structures; construction of parking lots (in consultation with the District Administration and Nagar Palika Parishad)
7.	**District Magistrate Office (DMO)**	In case of Nainital, DMO provides legal permission to work on the lake. Any person or organization/civic society/institution must take permission of DM before starting any work related to the lake.

Hydrological flows of Naini lake

Definition of Hydrological flow: According to General Multilingual Environment Thesaurus (GEMET) the characteristic behaviour and the total quantity of water involved in a drainage basin, determined by measuring such quantities as rainfall, surface and subsurface storage and flow, and evapotranspiration.

The water balance equation serves as a fundamental framework for understanding the hydrological flows of Naini lake. Inflow, the quantity of water entering the lake, comprises various components including surface inflow, subsurface inflow, inflow through drains, and direct precipitation. On the other hand, outflow represents the water leaving the system, which includes surface outflow through sluice gates, water evaporation, subsurface outflow, and pumping activities. Through this water balance equation we can understand the overall water balance, crucial for effective water resource management and environmental sustainability of Nainital.

Water balance = Inflow – Outflow

Inflow = surface inflow + subsurface inflow + inflow through drains + direct precipitation
Outflow = surface outflow through sluices gates + water evaporation + subsurface outflow + pumping

The hydrological flows of Naini lake is fairly illustrated in the following picture.

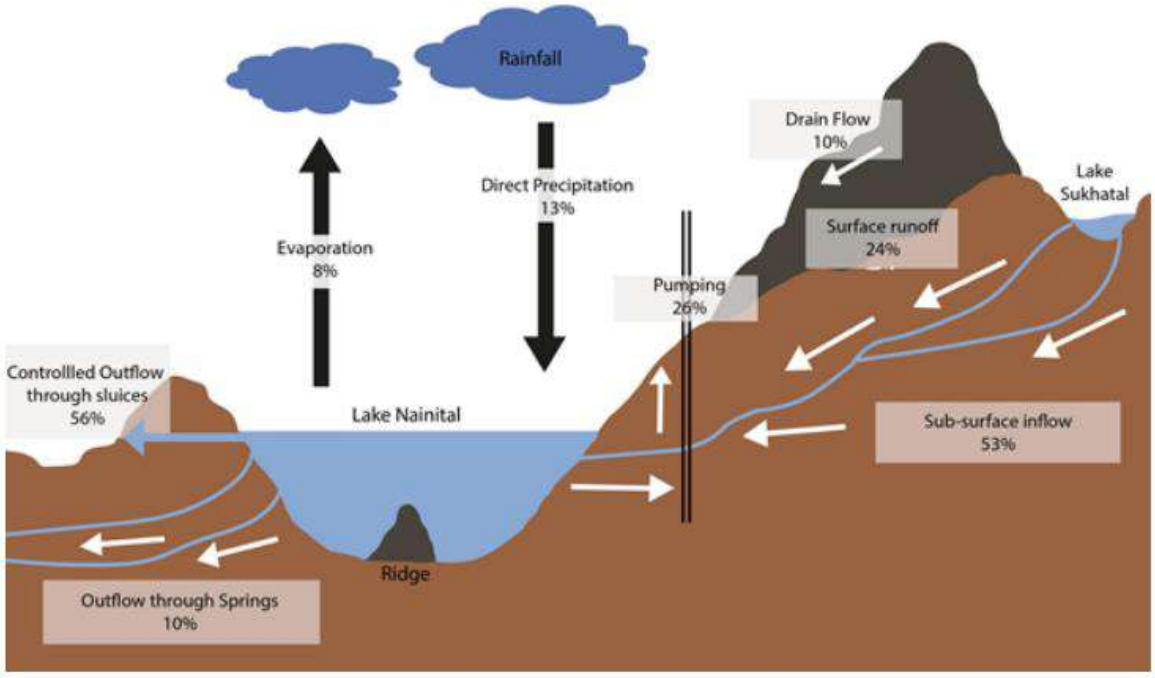


Fig. 9: Illustration of water balance of Naini lake

Listing of ecosystem services provided by lake

Definition of Ecosystem Services- Ecosystem services are the benefits provided to humans through the transformations of resources into a flow of essential goods and services (Constanza et al. 1997).

Lake and its catchment offer a variety of ecosystem services. After interacting with concerned departments, people and on the basis of secondary literature, some ecosystem services were identified.

Identified services were further classified into regulatory, provisional, supporting and cultural services based on the nature of service.

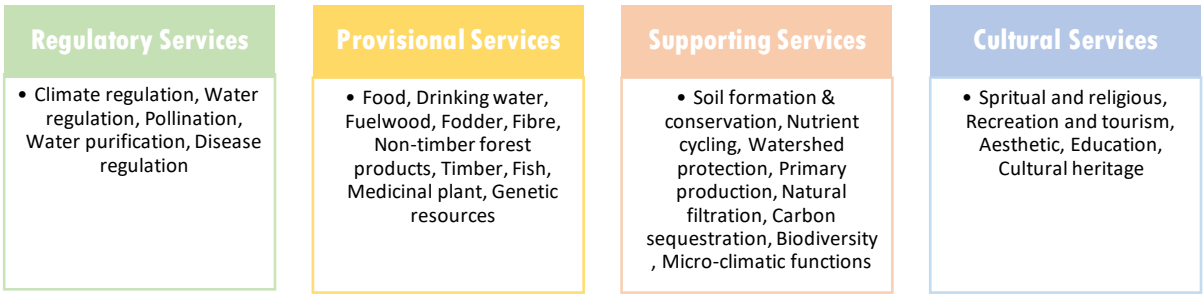


Fig. 10: Ecosystem services provided by Naini lake and its catchment

Community's dependence on water resources

It is evident from the literature that there is a significant dependence of community on Naini lake for various purposes including domestic, commercial and institutional needs, which underscore the lake's pivotal role in sustaining economic activities and daily life in Nainital. Consequently, this study was primarily dedicated to unravelling the intricate dynamics of the community's reliance on the lake, delving into aspects such as water demand, supply, availability, and quality. The findings underscore the heavy reliance on Naini Lake for commercial ventures, and household consumption, underscoring its indispensable role in both economic and domestic realms (Figure 11). While a small percentage of respondents do not depend on Naini Lake, suggesting potential alternative water sources (springs). Moreover, the dependence of commercial and institutional sectors on Naini Lake underscores its critical role, emphasizing the broader implications of any alterations in its water availability for the entire community. The comprehensive report pertaining to this aspect is provided in Annexure 2.

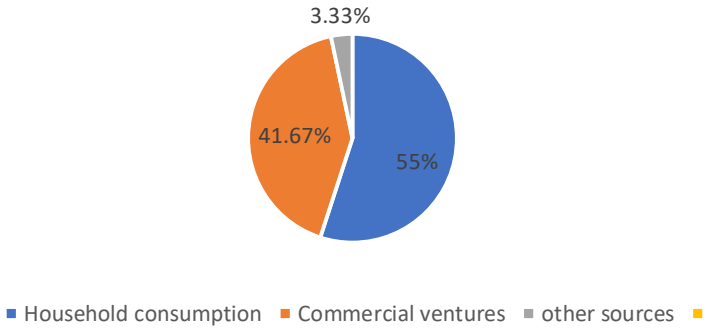


Fig. 11: Reliance on Naini lake as water source

Risks perceived by stakeholders

A comprehensive multi-risk assessment was conducted for Nainital city using a meticulously structured questionnaire to gauge the concerns of stakeholders. The risks identified encompassed various dimensions including natural hazards, socio-economic challenges, environmental issues, and regulatory constraints. The study illuminates the differences in perceived risk among stakeholders, even when facing similar conditions.

Among the risks identified as surpassing the average in the risk matrix were landslides, health crises, earthquakes, in-migration pressures, poorly managed stormwater systems, flash floods, and livelihood crises. Conversely, risks deemed below average included changes in land-use and land-cover, declining lake levels, urbanization pressures, pollution, biodiversity loss, improper solid waste disposal, water resource scarcity, and inadequate water supply. This comprehensive assessment underscores the diverse

array of risks faced by stakeholders in Nainital and emphasizes the need for tailored risk management strategies to address their specific concerns. The detail study regarding this aspect is presented in Annexure 3.

Impacts of anthropogenic activities on water resources

The anthropogenic activities in Nainital have significantly impacted the lake, springs and recharge zones, consequently altering the hydrological flows in the region. The degradation of natural habitats due to urbanization, deforestation, and improper waste management, construction in recharge zones has led to a decline in the recharge of groundwater, affecting the flow of springs that feed into the lake. Furthermore, the lake has been adversely affected by over-abstraction, siltation, and heightened pollution stemming from untreated sewage, leading to eutrophication. This exacerbates the disruption of the hydrological balance. This alteration in hydrological flows not only impacts the availability of water resources but also exacerbates the risk of floods and landslides due to changes in runoff patterns. Addressing these anthropogenic impacts is crucial for restoring the hydrological equilibrium of Nainital, ensuring sustainable water management practices, and safeguarding the ecological integrity of the region.

(The findings of objectives 4 and 5 are consolidated as they mutually reinforce each other's outcomes.)

Objective 4: To develop a deeper understanding of critical water zones and help identify areas critical to water recharge.

Objective 5: Mapping of critical water zones.

Key activities

1. **Identification, mapping and significance of critical water zones of Naini lake catchment**
2. **Identification, mapping and significance of springs in hydrological dynamics of Nainital**
3. **Importance of Heritage drainage system**
4. **Evaluate the status of recharge zones through Land Use Land Cover (LULC) change in Nainital.**

The complex interrelationships between critical water zones, springs, drainage systems and land use/land cover (LULC) become important when holistic water resources management is required in the region. Such deep understandings always help to understand the exact status and vulnerabilities of water resources. Using this information, we can strategize policies to protect water resources and promote sustainable development in Nainital and its surrounding areas. The important critical water zones, springs, drains and LULC pattern of Nainital are described below.

Identification of critical water zones

Understanding of the areas critical to water recharge of the Naini Lake is essential for ensuring its sustained health and vitality. Recharge zones refer to areas where water infiltrates the ground and replenishes aquifers, ultimately contributing to the maintenance of water levels in lakes and springs. In the context of Naini Lake, identifying and mapping these critical water zones is crucial for safeguarding the lake's hydrological balance and mitigating the risks of lake level depletion.

With the help of geological survey and spring mapping, the probable or potential recharge areas were mapped around the town. In case of Naini Lake, there are about 13 large-small recharge areas within the catchment (table 7), surrounded by thick dense forest of oak and pine.

Table 7: List of identified recharge zones of Naini lake catchment

S. No.	Name of recharge zones	Area (Square metre)
1.	The Fair Light	688
2.	Staff house *	1,691
3.	Birla VidyaMandir	6,155
4.	Golf Course*	15,707
5.	Governor House	15,546
6.	Forest View Point	3,162
7.	Tiffin Top*	812
8.	Sherwood parking	945
9.	Ayar Jungle	3,078
10.	Sukhatal	21,467
11.	ATI	3,860
12.	Metropole	3,793
13.	Flats	22,163
	TOTAL	99,067

Significance of critical water zones

The most important part of any lake hydrology (which is fed by drains and springs and not by any big river or glacier), is its probable/potential recharge areas within or outside the catchment. Recharge areas collect the rain water and gradually allow it to percolate in underneath geology. This percolated water is stored in rock cavities, pore spaces, fractures, joints etc. In brief, this water recharges the ground water i.e. aquifer. Aquifer is an invisible storage of water, wherever the aquifer level intersects with the surface of the earth, water emerges in the form of a spring or springs. These recharge areas not only feed the springs in the area but also keeps the lake alive with some base flows and underwater springs.

Approximately, 99067 sq.m. of land is recharge area, spread across the town. Due to the changes in land use and land cover, these recharge areas are under threat of encroachment and to some extent, complete disappearance. Urbanization and concretization are taking toll on this town as the number of residents grow, infrastructure need and sometimes luxury is satisfied by encroaching in such recharge areas as they are vacant depressed grounds.

Fig. 12: Geo tagging of recharge zones of Naini lake catchment.

Any recharge area stores water 2 to 3 months after the monsoon depending on the size and underneath geology; rest of the year, about 7 to 8 months, it remains dry. Such few places are used as playing areas in dry season. Most of these recharge areas are hidden within the forest covers, even the hoteliers have kept the areas untouched knowing its importance. But some areas which are easily accessible are being encroached severely with complete ignorance towards its necessary existence. Encroachment type is dominantly of concretizing the area for house construction or for parking or to make sports court. If the concretization of these areas takes place for any reason like, domestic, commercial or private, it will directly affect the water supply to the lake. Areas such as Sukhatal, Metropole parking, Sherwood School Parking, parking on flats are either severely degraded, reducing the recharge capacity or under tremendous human pressure/interventions.

Identification and mapping of springs

The identification and mapping of springs in Nainital hold paramount importance due to their significant contribution to the region's water supply, ecosystem health, and cultural heritage. Springs serve as natural outlets for groundwater, often emerging as vital sources of freshwater for both human consumption and ecological sustenance. In Nainital, where water resources are precious and vulnerable to various stressors, understanding the distribution and characteristics of springs is essential for sustainable water management practices.

Currently, dependency on spring is mainly for drinking water purpose. People living in surrounding areas are willingly dependent on these springs for drinking water purposes. Beneficiaries are not treating this water except in the months followed by rain when the mud content increases. For rest of the year springs are with appropriate water quality. Over the years, municipality also looked into this, and some concrete tanks were constructed near each locality in which spring water was brought through pipes, as most of these springs are located high in hills and accessibility is quite risky. Recharge areas are the most important factor that keeps the springs alive. Any interference with the land use of the recharge area directly hampers the discharge of spring. Most spring sources in the town have become seasonal or showing low discharge. Some spring sources have completely dried. At present, In Nainital, 2% supply of water demand is met by springs. However, 9 springs were identified in Naini lake catchment. Table 8 illustrates the name and status of springs.

Table 8: List of springs in Nainital along with their status

	Spring	Earlier status	Current status
1	**Spring Field**	**Perennial**	**Perennial**

2	**Near Bhabhar Hall**	**Perennial**	**Dry**
3	**Chunadhara**	**Perennial**	**Dry in summer**
4	**Pardadhara**	**Perennial**	**Perennial**
5	**Rajpura**	**Perennial**	**low discharge in Feb-June**
6	**Near lake view**	**Perennial**	**low discharge in Feb-June**
7	**Near Bhabar Hall**	**Perennial**	**Very low discharge**
8	**Near Spring field Cottage**	**Perennial**	**Perennial**
9	**Near Mount Rose**	**Perennial**	**Dry in summer**

Mapping these springs (Figure 13) facilitates the delineation of recharge areas, aiding in the protection of groundwater sources. Moreover, springs play a crucial role in supporting local biodiversity, serving as habitats for diverse flora and fauna. Culturally, many springs in Nainital hold religious and historical significance, further underscoring the need for their preservation and sustainable utilization.

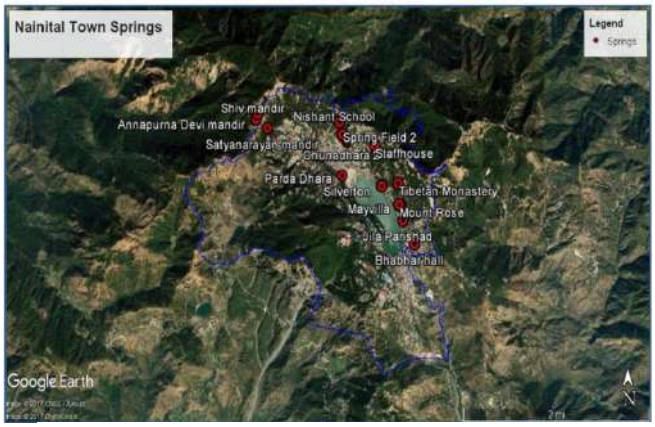


Fig. 13: Geo tagging of springs in Nainital

Heritage drainage system of Nainital

Lake is directly or indirectly fed by 79 km drainage network (consists small and large drains) in the catchment of lake (figure 14). The drainage system of Nainital aimed at speedy and effective drainage of the hillsides and was designed slope instability and geo-environmental issues of the area around Nainital with great care. The system has been crucial throughout history as settlements and town developed. The comprehensive drainage system was constructed during the British era and always being an integral

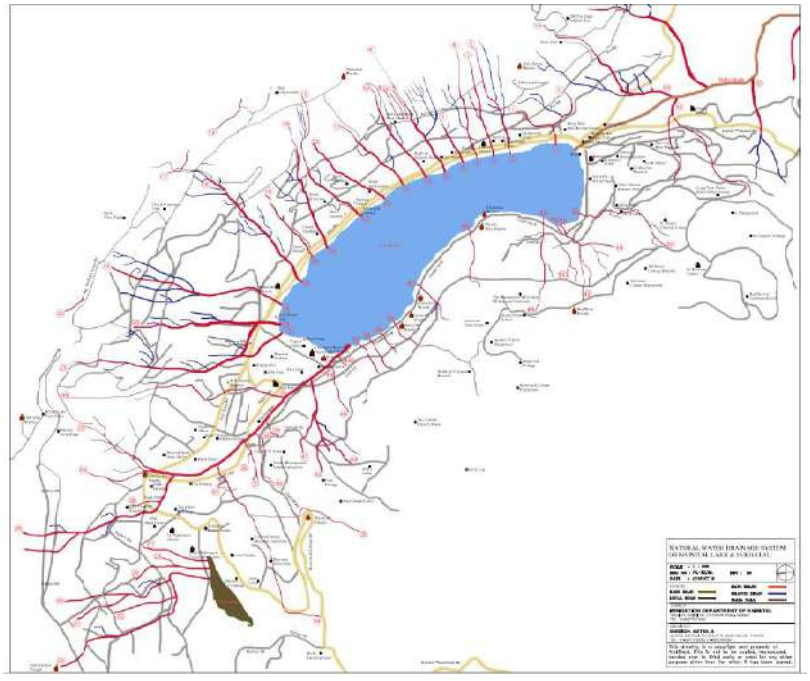


Fig. 14: Drainage system of Nainital city

***Source: Irrigation Department of Nainital**

part of the structural foundation of the city. There are 26 major drains including the 2 perennial ones feed the lake. These drains are arteries and veins of the town and help to channel the surface flow and avoid landslides. Actually, this drainage system came into existence only after the 1880 landslide. The whole drainage system was divided into compartments/systems (like Sher-ka-Danda system, Bara Nala system, Ayarpata system and System beyond the lake basin) and each system was meticulously inventoried for record-keeping and efficient monitoring.

Land Use Land Cover Change (LULCC) in Nainital

LULC patterns, encompassing urban areas, forests, agricultural lands, and other land uses, influence the dynamics of recharge zones, springs, and drainage systems. Urbanization and deforestation can alter surface runoff patterns, impacting groundwater recharge rates and water quality. Mapping LULC provides essential information for assessing land use changes and their implications for water resources. In present study Land use land cover LULC was divided into three classes, namely forest, urban, and open vegetation, where urban was given value of 3 since it has higher impact on water resources and forest was given the lowest rating 1. It was found that in the study area, forest area occupies approximately 31km^2, while urban areas and open vegetation is spread over across 1.78 km^2 and 0.99 km^2, respectively. Maximum settlement (urban area) was observed near the lake (Fig 15).

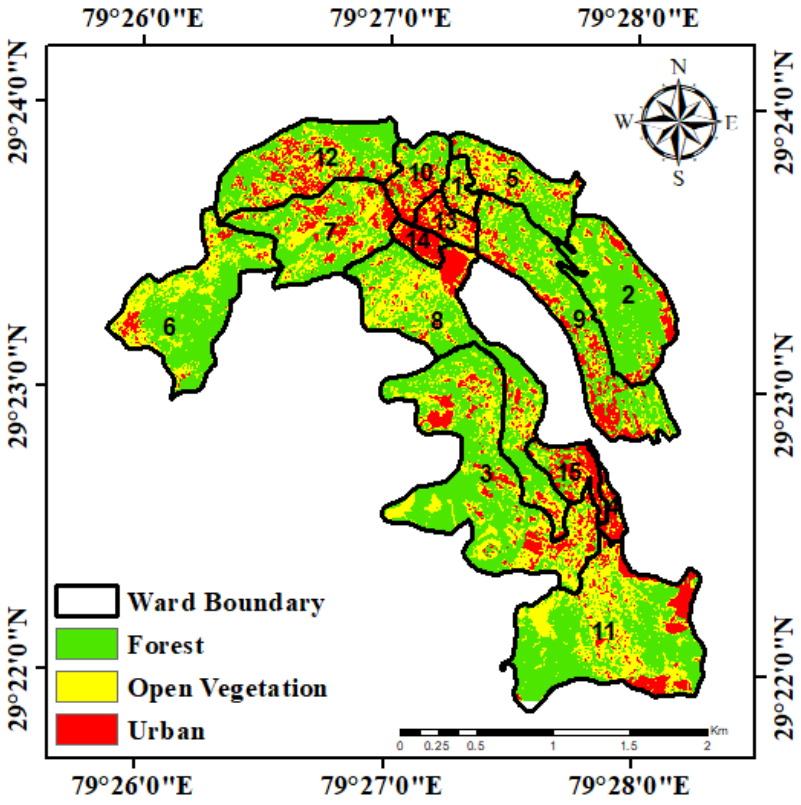


Fig. 15: LULC of Nainital as indicator of sensitivity

The observed trend of increased concretization, encroachment in catchment areas, decreased vegetation/forest cover/open land/water bodies in LULC patterns of Nainital highlights the urgent need for sustainable land management practices and land use policies. Strategies aimed at preserving green spaces, promoting compact urban development, conserving springs, maintain drains and enhancing ecosystem resilience can help mitigate the adverse impacts of land cover change and ensure the long-term sustainability of critical water zones of this beautiful lake.

Objective 6: Water Vulnerability Assessment of different wards in Nainital.

Water management is a growing concern for Himalayan cities. Population growth and climatic variability are exuberating the impact on surface and underground water supply. Understanding the causes and the extent of water vulnerability is required for developing effective strategies for water insecurities. This objective was focused on understanding the water vulnerability of Nainital city at ward level using GIS modelling approach.

Key activities

1. Develop a theoretical framework by identifying the indicators.
2. Develop methodology for vulnerability assessment.
3. Current demographic trend of the city
4. Source of drinking water and water supply system of Nainital.
5. Estimation of Water Vulnerability Index.

Theoretical framework

To assess the water vulnerability of the different wards inthe area, it was essential to select appropriate indicators thatwere substitutions of the component's exposure, sensitivity,and adaptive capacity. The proposed method included seven main indicators (land use land over, slope, population density, elevation, land surface temperature, distance to road, and distance to lake) to evaluate the vulnerability of 15 wards within Nainital town. Weights were provided to the indica- tors using AHP analysis and maps were produced that showed vulnerability categories within the wards using GIS spatial analysis tools. Following table shows the functional relationship with vulnerability.

Table 9:Indicators and their functional relationship with vulnerability

Dimension	Indicator	Description	Functional relationship	References
Exposure	Land surface temperature	Surface temperature is a proxy for temperature and high value reflects higher exposure. Warming is detrimental for society and water	Positive	(Pandey et al., 2014; Omerkhil et al., 2020)
Sensitivity	Population density	Sensitivity due to the population pressure. Population density is proxy to resource availability	Positive	(Lee and Choi, 2018; Sekhri et al., 2020)
	Land use land cover	Sensitivity due to urban, forest, and open area	Positive	(Koech et al., 2020)
	Slope	Sensitivity due to steeper slopes	Positive	(Lee and Choi, 2018; Guptaet al., 2020; Sekhri et al.,2020)
	Elevation	Sensitivity due to topography. Higher elevation requires better infrastructure and high pressure for water distribution	Positive	(Gupta et al., 2020; Sekhri et al., 2020)
Adaptive Capacity	Distance to lake	Distance to lake is proxy for infrastructural availabilityof water and more the distance, high the vulnerability	Negative	(Das et al., 2020)
	Distance to road	Distance to lake is proxy for availability of water and themore the distance, the higher the vulnerability	Negative	(Jamshed et al., 2020c; Jha and Gundimeda, 2019; Pandey and Jha, 2012)

Methodological Framework

Methodology used for mapping water vulnerability is graphically presented in figure 16.

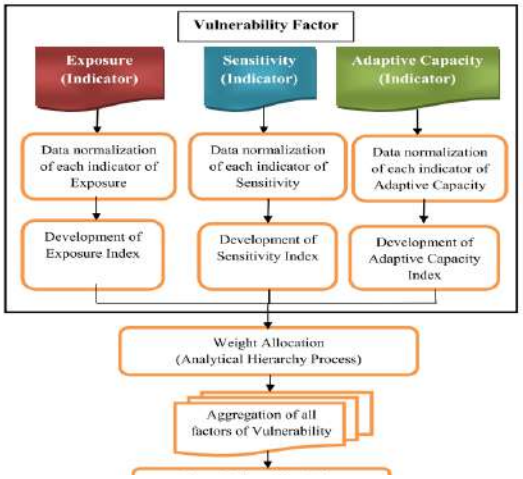


Fig. 16: Methodological framework used for mapping water vulnerability

Current demographic trend of the city

The analysis of population data shows that maximum population density was obtained for Harinagar Ward, and the least population density was obtained for Sree Krishnapur Ward (Table 10). Increase in population has a direct impact on the water resources, as high population requires more water for domestic purposes and would lead to put more pressure on the water resources.

Table 10: Demographic features of the fifteen wards of the city

Ward name	Population	Distance to lake			Ward area (km^2)	Population density (km^2)
		Minimum	Maximum	Mean		
Sree Krishnapur	2317	607.85	1821.58	1300.92	0.89	2590
Harinagar	2409	135.65	712.99	512.57	0.05	48584
Tallital Bazar	2310	16.96	561.37	203.06	0.13	17187
Rajbhawan	3172	75.83	1138.13	566.21	0.98	3236
Sher ka Danda	3481	220.44	713.20	474.79	0.46	7496
Narayan Nagar	2524	1174.44	2299.95	1752.23	0.56	4509
Upper Mall Road	3364	16.96	568.75	227.37	0.59	5726
Shukhatal	3384	541.03	1587.53	975.41	0.46	7403
Nainital Club	2623	465.62	917.08	690.59	0.16	16406
Snow View	3072	372.28	856.11	592.63	0.26	11679
Sainik School	2241	767.38	1710.04	1276.88	0.48	4663
Mallital Bazar	2479	180.25	570.01	369.24	0.06	40232
Awagarh	2391	84.78	508.99	317.99	0.09	27374
Ayarpata	2482	0.00	736.21	279.30	0.67	3704
Staff House	3128	288.27	700.38	496.64	0.07	47881

Source: Nagar Palika for population related parameters; area is estimated through remote sensing

Source of drinking water

Naini Lake

Lake water from wells adjoining the lake through Lake Bank Filtration (LBF)

(76% of total supply)

Level of treatment- natural filtration + Chlorination

Sukhatal -sub-catchment

Ground storage water

(22% of total supply)

Level of treatment- only Chlorination)

Spring water

(2% of total supply)

Level of treatment - no need of treatment

Water supply system

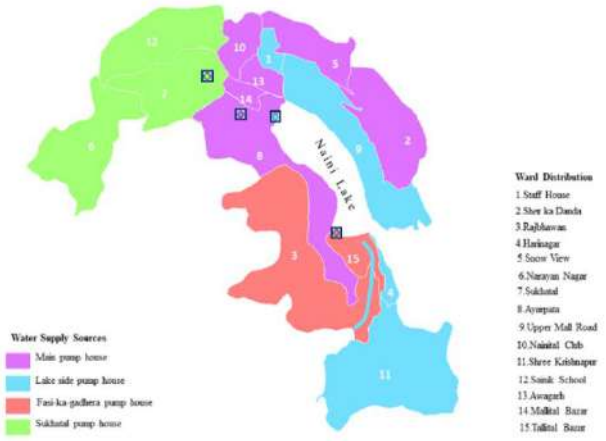


Fig. 17: Major sorces of water in Nainital

Fig. 18: Water supply system of Nainital

At present, 15 tubewells are installed, 11 are at lakeside while, 4 are installed on the lake-bed of Sukhatal. These tubewells are producing 8.0 mld (million litre per day) water while, the rest 0.167 mld is drawn from the springs. There are four water pump houses and the whole city is divided into twenty water supply zones. The specifics regarding the pupped water from 15 tube wells can be found in Annexure 4 (Source: Jal Sansthan, Nainital).

Water vulnerability in Nainital

The results indicated the overall moderate vulnerability in most of the wards of the town; however, high value of vulnerability was observed in Mallital, Awagarh, Nainital club, Staff House, Tallital, and Harinagar wards, primarily due to high sensitivity in these wards (Table 11).

Table 11: Dimensions of vulnerability in various wards

Ward name	Exposure	Sensitivity	Adaptive capacity	Vulnerability	Rank
Sree Krishnapur	0.014	0.359	0.234	0.257	11
Harinagar	0.015	0.473	0.388	0.298	14
Tallital Bazar	0.011	0.424	0.414	0.225	7
Rajbhawan	0.009	0.316	0.340	0.153	1
Sher ka Danda	0.006	0.400	0.367	0.221	6
Narayan Nagar	0.008	0.314	0.209	0.215	5
Uppar Mall Road	0.008	0.378	0.406	0.182	3
Shukhatal	0.009	0.345	0.302	0.204	4
Nainital Club	0.011	0.421	0.312	0.275	13
Snow View	0.007	0.415	0.356	0.246	9
Sainik School	0.010	0.352	0.251	0.237	8
Mallital Bazar	0.014	0.444	0.418	0.249	10
Awagarh	0.014	0.461	0.404	0.273	12
Ayarpata	0.008	0.350	0.399	0.160	2
Staff House	0.009	0.483	0.352	0.316	15

The focus of this study was to determine the water vulnerability at ward level, with its aim to guide the policy makers and the government to reorient the policies in terms of improved distributional and infrastructural support to reduce water wastage, awareness campaign for optimum use of water, and provisions for water harvesting and develop appropriate adaptation strategies according to the vulnerability level in each ward. The reduced water vulnerability would provide better services to the tourists and therefore improve the economic opportunities to the locals.

Objective 7: To develop citizen science initiatives through schools, colleges and citizen groups and catalyse such groups to influence good water policy.

Citizen science initiatives play a crucial role in influencing effective water policy. This objective was an effort to engage the communities in monitoring, data collection, and advocacy efforts. These initiatives empower citizens to actively participate in safeguarding water resources and advocating for sustainable policies. By harnessing long-term data monitoring and collection facilitated by platforms like Automatic Weather Station (AWS), citizens are empowered to contribute valuable insights into weather trends over time in Nainital. The crowd sourcing data collection approach not only generates valuable data but also fosters public awareness and ownership of water issues. Furthermore, citizen scientists collaborate with policymakers, sharing their findings and insights to inform evidence-based decision-making.

Key activities

1. **Long term data measurement and monitoring by citizens through Automatic Weather Station (AWS).**
2. **Involving community in data collection.**
3. **Spreading awareness through workshops with diverse stakeholders.**

Long term data measurement and monitoring by citizens

Long-term data measurement and monitoring are critical components of citizen science initiatives. By providing citizens with access to Automatic Weather Station platform, this initiative empower individuals and communities to actively participate in collecting essential environmental data. Automatic weather stations offer user-friendly interfaces and real-time data collection capabilities, enabling citizens to monitor various parameters such as temperature, precipitation, humidity, and wind speed. By engaging in continuous data collection over extended periods, citizens contribute valuable insights into local weather patterns.

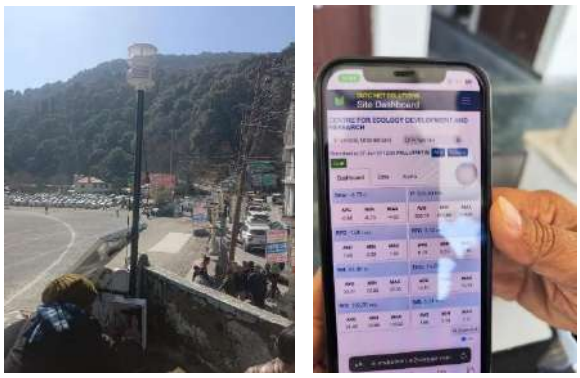
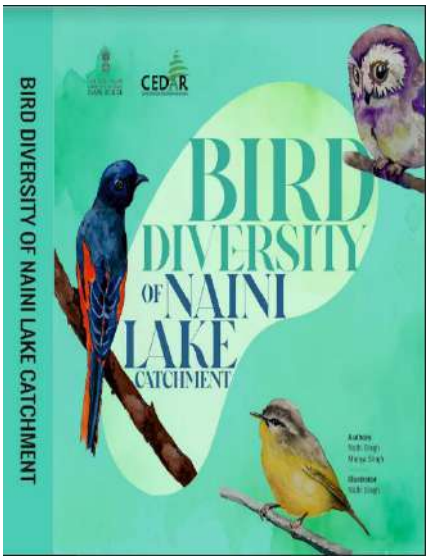


Fig. 19: AWS, installed in District Sports Academy building, Nainital.

Under this project two AWS have been installed in Nainital town by team CEDAR. The installation points are District Sports Academy (DSA) building and Sainik School (Figure 19). Any one can easily access the weather data of Nainital city by clicking on this link and filling the given login credentials.
https://envirofront.m2mlogger.com/sstc/LiveMap
Username: cedarhimalaya@gmail.com
Password: Nainital@123

Community involvement in data collection



Various studies indicate that birds are good indicator of environment health because they occur in almost all habitats and are sensitive to environmental change. Gathering baseline data on the presence and migratory patterns of birds allowed us to gain valuable insights into the local ecosystem of Nainital. As part of our objective to fostering community-led projects, we embarked on a project to document the avian diversity of the Naini Lake catchment area in the form of a book. The information and data presented in this book have been meticulously compiled from contributions by citizen scientists, bird watchers, and photographers from Nainital. This collaborative effort not only highlights the rich biodiversity of the region but also underscores the importance of citizen engagement in environmental conservation and research.
Since such studies are lacking, this document will act as a baseline for the future researchers focus on rapidly urbanizing and changing landscape of Nainital due to anthropogenic and climate change scenarios. This kind of initiative empower citizens to be active participants in conservation and environmental management, thus creating collective leadership and ultimately helping to safeguard the future of the ecosystems they inhabit.

Awareness programs

The CEDAR team took proactive steps to raise awareness and facilitate knowledge exchange by hosting multiple workshops in collaboration with stakeholders. These events served as platforms for fostering dialogue, sharing expertise, and formulating effective dissemination strategies. The following sections provide detailed accounts of each workshop and its outcomes.

Workshop 1 - Expert consultation on knowledge exchange and research dissemination strategies

The deliberations and experts (leading government organizations, universities, civil society organizations, community leaders, subject experts) discussed and shared their insights on following action points for consideration. Key area of concern included: -

Poor maintenance of drains; High institutional overlaps, hence lack of responsibility; Concern about feasibility of aeration; Lake pollution; Improvement of larger community for awareness (Schools and sports community); Car parking and pollution; Developing spring Janam patri; Jal police; Celebrate 18th September as clean the lake day; Promote ‘Catch the rain’ initiative and more focus on Nature Based Solution.

Workshop 2 – Knowledge Dissemination workshop

The open discussions held during the workshop yielded several key insights and points for consideration. Key points of concern included -

1. Use previous study for bathymetry study to correlate the present information.
2. Study on carrying capacity of Himalayan towns should be done.
3. Concretizing the footpaths in Nainital should be regulated.
4. We should focus more on demand management issues.
5. Existing scientific information should be translated nicely for citizen use.
6. Need for more active and engaged citizens group.
7. Interdisciplinary research is important with a bottom down approach.
8. Drains are an important part of Nainital's hydrology. It should be managed properly.

These grassroots approaches not only enhance scientific understanding but also fosters a sense of ownership and responsibility among citizens. By bridging the gap between communities and government agencies, citizen science initiatives can catalyze positive changes in water policy. Ultimately, the collective efforts of citizen scientists serve as a powerful force for shaping policies can prioritize the protection and preservation of water resources for current and future generations of Nainital.

(The findings of objectives 8 and 9 are consolidated as they mutually reinforce each other's outcomes.)

Objective 8 - To coordinate between schools, colleges, research institutions, citizen groups, and the district administration and policy–makers, in order to help develop effective networks around water supply and policy.

Objective 9 – Influence Policy at Local, State and National level.

A concerted efforts have been made to foster collaboration among schools, colleges, research institutions, citizen groups, district administration, and policymakers. The overarching goal was to cultivate robust networks focused on enhancing water supply and policy frameworks.

Key activities

1. **Promoting judicious use of water through RWH.**
2. **Articulation of policy brief by assessing the water harvesting capability of four cities of Uttarakhand**
3. **Develop water focused website for Nainital to disseminate research findings to the public.**
4. **Strategic engagements with local administration, citizens, and policy influencers through workshop.**

To achieve these objective, several initiatives have been undertaken. Firstly, efforts have been directed towards promoting the judicious use of water by advertising rainwater harvesting (RWH) practices. Additionally, a policy brief has been articulated to facilitate informed decision-making. Furthermore, a dedicated website centered on water-related issues in Nainital has been established to serve as a hub for information dissemination and community engagement. Moreover, science dialogue focusing on water recharge areas has been conducted to encourage knowledge exchange and collaboration among diverse stakeholders. The following section outlines the specific details of these initiatives.

Assessing the potential of Roof Water Harvesting (RWH) in Nainital

During our study we uncovered the considerable potential of Rain Water Harvesting structures in Nainital. The results revealed that RWH structures can be installed at hotels, commercial buildings making them self-reliant in the hill town of Nainital. It will help in maintaining the lake level as stored water can be used for general purposes. The RWH potential estimated for different scale predicts the surface runoff can be captured and stored for the future use. The calculation shows that, if RWH structures are installed in 25% of built-up areas, during the monsoon the supply from Lake can be catered by storing the rain water (Annexure 5). Also, hoteliers should install rainwater harvesting structure to store the rainwater to reuse it in toilets, washing and gardening purposes which can further lessen down the stress on lake for supply during the peak season. The Rainwater Harvesting Structures can make the hill town sustainable in terms of water conservation and can help the authorities to maintain the lake level throughout the year. The detail of the study is available on www.nainitalwater.com and www.cedarhimalaya.com.

Policy Brief

The policy brief outlines the "Catch the Rain" campaign and provides an assessment of four cities – Nainital, Haldwani, Dehradun, and Mussoorie – focusing on their capacity for implementing sustainable water management practices, by adopting the RWH techniques. The detailed document is attached as Annexure 4 for reference.

Website

The CEDAR team has curated an invaluable resource in the form of website www.nainitalwater.com. This comprehensive website offers unrestricted access to a wealth of information pertaining to Nainital's water dynamics. Visitors can explore diverse sections such as an extensive repository housing weather data and literature dedicated to Nainital; direct

links to pivotal water-centric government and global initiatives, and detailed insights into the hydrology specific to Nainital. Additionally, the website serves as a centralized hub for all research findings generated through this project, ensuring transparency and accessibility for stakeholders and the wider community alike.

Strategic engagements

To influence decision makers and policy influencers a workshop was jointly organized by the Lake Development Authority (LDA) and CEDAR. Member of Legislative Assembly (MLA), Nainital, Commissioner Kumaon, District magistrate Nainital, Secretary Lake Development Authority and other senior officers of government department along with citizens participated in the workshop. The main focus of this workshop was "Sukhatal Rejuvenation Plan".

The discussion encompassed several key aspects, notably focusing on the ecological and hydrological importance of Sukhatal lake. Delving into its significance within these contexts, the conversation extended to the materials utilized in its construction. Additionally, for the revival of Sukhatal, experts emphasized the implementation of nature-based solutions and soft landscaping techniques. It was strongly advocated to ban any practices leading to the concretization of the lake bed, ensuring the preservation of its natural integrity and functionality.

Knowledge Products

Research Paper

1. (Published) Climate change water vulnerability and adaptation mechanism in a Himalayan City, Nainital, India. Environmental Science and Pollution Research. Link - **https://doi.org/10.1007/s11356-021-15713-5**
2. (Published) State of Indian Northwestern Himalayan lakes under human and climate impacts: A review. Ecological Indicator. https://doi.org/10.1016/j.ecolind.2024.111858

3. (Under review in Journal Water Policy) Impact of Institutional Overlapping on Water Governance of Himalayan City, Nainital, India
4. (Prepared for imminent submission to Cities Journal) City Profile: Nainital

Popular articles

1. An article "Nainital's water woes: Every drop of rain counts" has been published on India Water Portal which emphasized "Catch the Rain" https://www.indiawaterportal.org/author/nidhisingh

2. An op-ed "Uttarakhand floods: Why abnormal weather is the new normal" has been published on online platform which discussed the climate change impacts https://mojostory.com/pov/uttarakhand-floods- why-

Dissertation

1. Risk Evaluation and its Prioritization in the Lesser Himalayan City, Nainital
2. Impact of urbanization on water resources & opportunity of RWH structure in Nainital

Note: Other knowledge products (infographic, display materials and video documentary) are available on the website www.nainitalwater.com.

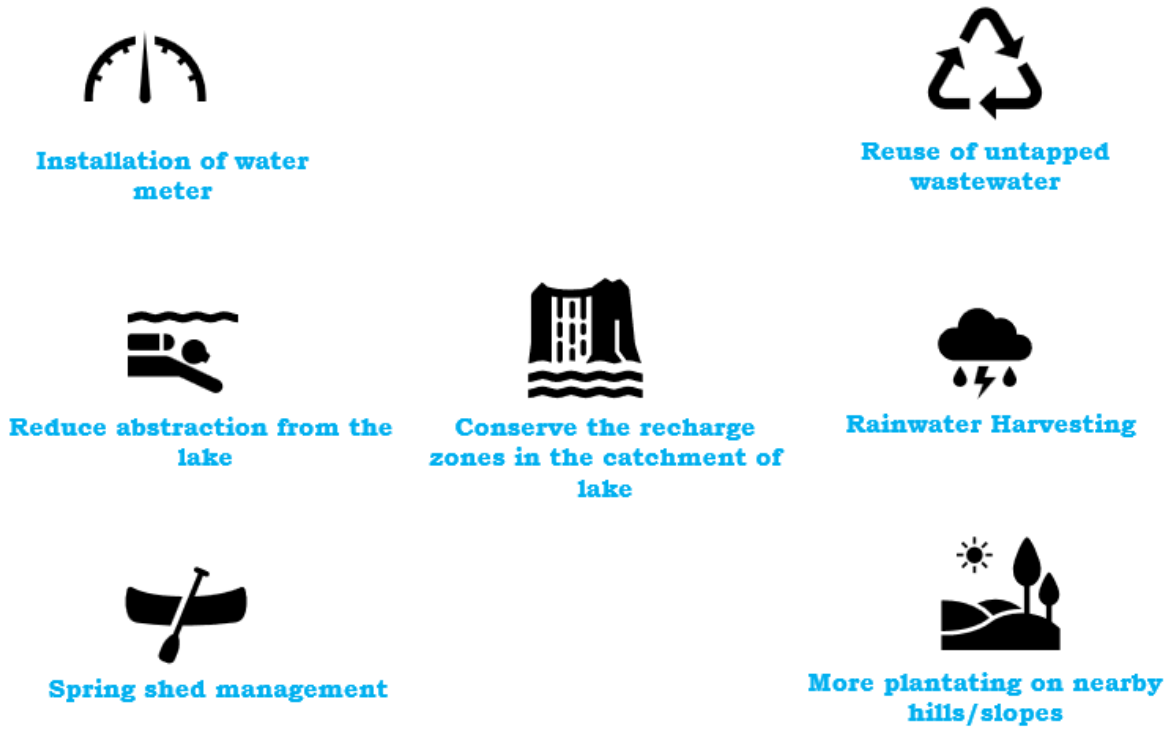
Achievement

Dr. Vishal Singh was included in the four members committee formed for the rejuvenation of Sukhatal.

Owing to CEDAR's long-term commitment towards conservation of Nainital through evidence-based policy advocacy, Dr. Vishal Singh, Director Research was included in the four members committee. The others member of the committee includes Prof. Ajay Rawat (Environmentalist, Historian), Heritage conservationist Mr. Anupam Shah and Prof. Charu C. Pant (Geologist).

Synthesis & Recommendations

The synthesis of Nainital-specific climate adaptive water management solutions as well as recommendations for future studies and research, are derived from the culmination of insights gleaned from multiple meetings and workshops involving a diverse range of stakeholders. These stakeholders likely include local government officials, environmental experts, community leaders, academics, engineers, policy influencers, and residents of Nainital and its surrounding areas. Through collaborative discussions and knowledge exchange, a robust comprehension of potential recommendations for water management in Nainital has been cultivated.



Recommendations

1. Instead of relying solely on engineering solutions we should prioritize nature-based approaches to preserve Nainital's delicate ecosystem.
2. CEDAR team highly recommended the use of clay materials over concrete at Sukhatal to facilitate percolation and benefit aquifers.
3. Ensure proper maintenance of Nainital's 79 km heritage drainage system to prevent disruptions to the hydrological cycle and reduce landslide vulnerability.
4. Clarify the roles and responsibilities of institutions to address the institutional overlaps impacting water governance in Nainital.
5. Address concerns regarding the feasibility of aeration.
6. Implement sewage treatment plants instead of direct dumping into the lake to safeguard water quality.
7. Keeping cultural background of Nainital in mind, we should foster collaborative efforts by involving informal institutions, schools, sports, and artist communities in research.

8. Engage with the community to implement spring shed management initiatives for spring revival in Nainital.
9. Encourage the adoption of RWH techniques in Nainital by leveraging the support of the "Catch the Rain" campaign initiated by the Government of India, in partnership with local institutions and communities.
10. Conduct a recent study to assess the carrying capacity of Himalayan towns, including Nainital.
11. Implement demand management strategies and promote eco-sustainable tourism practices to mitigate the impact of excessive tourist influx on natural resources and infrastructure.
12. Enforce strict regulations and policies to curb unplanned development and prevent encroachments on drains, recharge zones, and lake catchment areas.
13. Translate existing scientific information and data into accessible formats for citizen use.
14. Foster active citizen engagement to address water-related issues in Nainital.
15. Promote interdisciplinary research to protect biodiversity and water resources in Nainital.
16. Tackle both water quantity and quality concerns to ensure the long-term sustainability of Nainital's water resources.
17. Encourage the integration of gender-inclusive approaches in water management to address a wide range of perspectives and solutions.
18. Springs have historically served as vital sources of water supply since their discovery. However, currently, many springs have either dried up or are experiencing low discharge rates. This situation underscores the significant opportunity for implementing Spring rejuvenation programs through the application of the nine-step methodology of Spring shed management.

Suggestions for further work

1. Establishing a comprehensive monitoring network could contribute significantly to building a robust database of field observations pertaining to critical meteorological variables and hydro-ecological parameters of the lake. Such data would serve as a valuable resource for conducting in-depth scientific inquiries aimed at enhancing our understanding of the lake system. Additionally, leveraging the monitoring network and observational data would not only facilitate the sustainable management of the lake but also streamline the process of policymaking, ensuring more effective and informed decisions.
2. Further investigation into the ecological impacts of artificial aeration on aquatic life and biodiversity is recommended, particularly regarding the potential disruption of the ecological cycle within the lake due to the thermally mixed system. This research could provide valuable insights into addressing potential adverse effects on aquatic ecosystems and ensuring their long-term sustainability.
3. Further research is required which will integrate hydro-ecological and aquatic Eco dynamics to explore the intricate interaction between aquatic ecosystems and the hydro-ecological shifts occurring in the lake.
4. Looking ahead, it is recommended to integrate the model with the Aquatic EcoDynamics (AED) water quality module within GLM. This integration will offer enhanced insights into the impacts on aquatic ecosystems. Moreover, utilizing the developed GLM model will facilitate the evaluation of climate change effects on lake hydro-ecology.

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