Using Ecosystem Services in Source Water Protection – Two case studies in India

Case study of Bohal Spring and The Dal Lake

Master's Thesis in the Master's Programme Infrastructure and Environmental Engineering

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ABSTRACT

A small percentage of the earth's water is available as freshwater, out of which less than 1% is available for humans and can be used as a source of drinking water. Freshwater in lakes, rivers, and groundwater aquifers provide great values to the society. However, as a result of the human activities such as urbanization, climate change effects etc., these resources are being overexploited and are becoming polluted. Even though many water protection laws are enforced in many parts of the world and are included as one of the main goals in UN's SDG plans, water protection is complicated as it involves numerous stakeholders and thus many competing interests. Furthermore, the protection of water sources are typically based on the quality of the water from a drinking water perspective (i.e. the quality of water that is used as a source drinking water source). There is typically a lack of consideration given to the additional services provided by these surface water and groundwater ecosystems. There are numerous ongoing research studies that have been undertaken in order to identify and map ecosystem services. For example, the Millennium Ecosystem Assessment (MEA), The Economics of Ecosystems and Biodiversity (TEEB) and the Common International Classification of Ecosystem Services (CICES) frameworks are well known for evaluating ecosystem services. However, it is a tedious process to apply these Ecosystem Services frameworks for each drinking water source. With the intension of making the assessment easier and specifically tailored to drinking water source, Gärtner et al. (2022) developed a region-specific water system service (WSS) list. The aim of this study was to apply the concept of water system service (WSS) list developed to Gärtner et al. (2022) to two case study sites in India to see how the list can be adapted to other regions. In addition, the identified ecosystem services was integrated into a risk assessment of the drinking water sources.

In the results section WSS list, hazard list and risk assessment matrix for both the case study sites are presented. One new ecosystem service was identified for surface water ecosystem apart from WSS list. However, the results clearly illustrates that the WSS list can be transferred to other case study sites irrespective of geographical location and it provides an overview, and guidance on how to protect the drinking water sources.

Key words: ecosystem services, ES-frameworks, water system services, drinking water, risk management, risk assessment, hazard identification, water protective measures

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Acknowledgement

I would like to express my sincere gratitude to my supervisors Nadine Gärtner and Andreas Lindhe from Chalmers University of Technology, for their guidance and support throughout this project. Their feedback at every stage of the project has been insightful in shaping the direction of my thesis's aims and objectives.

I would also like to thank my examiner, Lars Rosen, for his valuable time and for his helpful comments during the project.

In addition, I would like to express my appreciation to my colleagues and friends for providing feedback and supporting me morally.

Finally, I would like to express my gratitude to my parents, Dr. K. G. Suresh Kumar, Dr. S. A. Sujatha and my family for always encouraging me throughout my academic journey.

Special thanks to my beloved uncle Prov. M. V. Srinivas Gowda, who is not with us today for always believing in me and supporting me throughout my scholastic journey.

Thank you all for your support.

Sincerely,

Suhani Kalinganahalli Suresh

List of acronyms

A list of acronyms used in the thesis, arranged alphabetically.

CICES – The Common International Classification of Ecosystem Services

DW – Drinking Water

ES – Ecosystem Services

MEA – Millennium Ecosystem Assessment

PES – Payment for Ecosystem Services

SW – Surface Water

TECHNEAU – Technology Enabled Universal Access to Safe water (research project)

TEEB – The Economics of Ecosystems and Biodiversity

WHO – World Health Organization

WSS – Water System Services

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1 Introduction

In this chapter, topic of the thesis is introduced. It describes the background and motives for the thesis topic. Aims and objectives are also presented in this chapter.

1.1 Background

Access to safe water is necessary worldwide and requires everyone's efforts. It is incredibly important to ensure that safe water is available to everyone as it plays a major role in for human health and the development of a communities. Only 3% of the earth's water is freshwater, out of which less than 1% can be used as a source for drinking water (DW) [1]. Freshwater ecosystems and groundwater ecosystems around the world are undergoing rapid changes due to increase in population and human interference with these resources. According to United Nations' UN-Water 2021 progress report, 21% of the water basins are experiencing changes in surface water covered area due to various reasons like flooding, drying up of surface water bodies etc. [2]. In many parts of the world, fresh water is increasingly threatened due to its open accessibility and the lack of legislation protecting it. Furthermore, humans are overusing groundwater and depleting groundwater levels unsustainably in many parts of the world [3].

Water protection is complicated since it affects a number of different stakeholders such as communities, government body, farmers etc, and competing interests typically exists. Furthermore, legal and regulatory frameworks can complicate the coordination of water management practices around the world [4]. Water resources and therefore water management are also challenged by uncertainty in global environmental change such as floods, drought, climate change etc., [5]. To effectively address these challenges, water management strategies must be developed collaboratively among all stakeholders, and despite all these complexities, source water is still protected only according to drinking water requirements.

Protecting drinking water sources can, for example, reduce the risk of exposing them to. However, protective measures may also provide other ecosystem benefits to biotic and abiotic components which are typically not accounted for. Protecting these biotic and abiotic components may be of great values and should thus be considered in combination with the source water protection and the contributions provided by these components to human well-being can be defined as ecosystem services (ES) [6]. There is misconception that water quality is a final ecosystem service [7]. Water quality, however contributes to variety of ecosystem services, from food to human health. A major obstacle to the mapping these ecosystem services into decision making processes of water management is due to lack of data and generalized framework [8,9].

Globally, different initiatives has been taken to identify and map the different ecosystem services nature provides to human well-being. Millennium Ecosystem Assessment's (MEA) ecosystem services (ES) framework represented a breakthrough in evaluating ecosystem services [10]. Later, The Economics of Ecosystems and Biodiversity (TEEB) presented a framework for capitalizing on biodiversity and analysing ecosystem risks in business [**Error! Reference source not found.**]. Using MEA's and TEEB's frameworks, the Common International Classification of Ecosystem Services (CICES) designed a revised ES framework that provides a more comprehensive assessment of ecosystem services (both biotic and abiotic) [11].

Even though there have been a few studies providing some guidance on how to practically identify and include ES while working on regional source water protections [13], linking the ES-framework to each of the water protection site would be tedious and time-consuming process, therefore it should be made easier, cost-effective and specially tailored to drinking water sources [9]. For this purpose, Gärtner et.al (2022) have developed a region-specific water system service list for the Swedish region and have demonstrated that it is feasible for drinking water source [6]. However, there is a need of applying the list to regions outside Sweden to evaluate if additional services should be added.

1.2   Aim and objectives

The overall aim of this study is to apply the concept of water system services introduced by Gärtner et al.(2022), to two case study sites in India in an attempt to identify how the list may be complemented and adapted to other regions. Additionally, the study aims to integrate the identified water system service list into the a risk assessment for the studied case study sites.

Specific objectives are to:
  a) Identify two suitable case study sites in India (one groundwater source and one surface water source).
  b) Perform a water system service assessment for the case study sites.
  c) Identify missing water system services for the studied sites by cross-checking with CICES.
  d) Identify hazards for both the case study sites and perform a risk assessment.
  e) Identify and evaluate possible water protective measures.
  f) Evaluate the list's applicability to other region besides Sweden for which it was originally developed.

1.3 Structure of work

In this study, the list of water system service list developed by Gärtner et.al (2022) is applied in case studies in other parts of the world to identify how the list can be adapted to other regions. For this purpose, 2 case study sites in India were identified. The choice of India was mainly based on the aim to find a region that differs to Swedish with respect to both natural conditions and human activities. In terms of diversity, India is recognized as one of the world's most megadiverse country with about 45,000 plant species and about 91,000 animal species [14]. As a result, 2 different case study sites are identified in the northern part of India to carry out the studies. Detailed description of these sites is provided in section 3.1 and 3.2.

The second part of the study focuses on identification of hazards along the entire drinking water supply chain, i.e. from catchment to consumer, and to assess the risk. This is done in order to incorporate identified water system services (WSS) into risk assessment of DW. The World Health Organization has concluded that the most effective way to guarantee safe water to consumers is not by testing only the final product, but rather by assessing the entire process from catchment to consumer [15]. In India, mainly end product assessment is applied by analysing the final drinking water quality [16]. Therefore, a combined hazard identification and risk assessment is performed for all identified water system services, including drinking water supply. The final part of the study includes an identification and recommendation of water protective measures based on risk assessment results.

1.4 Limitations

As both the case study sites are in India, the data has been remotely obtained through various technical papers, news articles, research on the case study sites and through Google maps. This might alter the precision of the results. Furthermore, the groundwater source case is located in between forest areas, and there is no information available on the location of contaminated areas. This affects the uncertainties related to the risk assessment results.

2 Theoretical Background

In this chapter, the theoretical background to some of the key concepts which are applied in this study are presented, i.e., ecosystem services (ES), ES-frameworks, water system services, hazards and risk assessment.

2.1 Eco system services

From the fresh air we obtain from plants to the microbes that help us with our waste degradation, there are many benefits humans obtain from nature. These are referred to as 'ECOSYSTEM SERVICES'. They are very much essential for human well-being and forms a major part of healthy ecosystems. Even though there have been discussions about ecosystem services for a long time, it is gaining popularity in recent times because it provides a means to show the benefits nature provides to humans. Initially MEA classified them into four categories: Provisioning services, regulating services, cultural services and supporting services [10]. The cascade model in CICES emphasizes the relation between ecosystem function, ecosystem, its connection with human well-being and defines ecosystem services as "the contributions that ecosystems make to human well-being" [11]. It follows a hierarchy to classify the ecosystem services and services are classified as provisioning services, regulating services (e.g., prevention of subsidence, climate regulation) and cultural services (e.g., aesthetic experience, recreation, entertainment). Provisioning services are goods that people can obtain directly from ecosystems, and these include services like food, water etc. A regulating service is one that a person can obtain through regulation of ecosystem process, and these include services like prevention of subsidence, climate regulation etc. Cultural services are non-material services such as entertainment, aesthetic experience, recreation etc. CICES does not recognize supporting ecosystem services such as soil formation, nutrient cycling etc. since they see them as foundation upon which all other ecosystem services rest. Using a forest as an example, provisioning services include timber, fruits, animals etc., which can be directly obtained from the forest, regulating services include climate regulation, water purification etc., and cultural services include aesthetic experiences, recreation etc. In this study, CICES' eco system service classification is used.

2.2 ES-frameworks

To systematically map ES, extensive work has been done on defining appropriate frameworks to facilitate assessment. "Ecosystem and Human Well-being", the first product launched in 2001 by Millennium Ecosystem Assessment, developed the ES-framework by focusing on how ecosystems altered by human beings are affecting people and their future [10]. It also focuses on

identifying and evaluating policy and management options to sustain ecosystem services, by collaborating with scientists and policy makers [10]. A detailed methodology is included for assessing and measuring the services, which includes indicators and metrices. The framework mainly focuses on the social and economic aspects of ecosystem services and helps evaluate ecosystem services by their contribution to human well-being.

Then, The Economics of Ecosystems and Biodiversity (TEEB) was launched in 2007 by United Nations Environment Programme (UNEP) to help decision-makers identify the benefits that ecosystems provide by adding economic value [**Error! Reference source not found.**]. A major focus of the framework was on the economic value of ecosystem services and cost of their degradation. By adding value to ecosystem services, it provides comprehensive analysis of their benefits and costs. Many economic evaluation techniques such as cost-benefit analysis, market evaluation is included in the framework which helps in decision-making process.

Later, the Common International Classification of Eco-System Services (CICES) was developed in 2013 by European Environment Agency to provide a common naming and classification system to evaluate final ecosystem services [11]. The framework provides a standardized way to evaluate ecosystem services across different sectors and disciplines which facilitates in communication and understanding. It mainly focuses on providing a common framework to assess ecosystem services, rather than evaluating their economic and social values.

In general, the MEA, TEEB and CICES frameworks help in assessing and valuing the relationship between ecosystems and human well-being but each one has different focus and approach.

2.3   Water system services

UN Water identifies 'lack of data' as one of the main barriers to properly manage ecosystems (i.e., freshwater, surface water, and frozen water) and their services. Despite the increase in interest in the topic, there have been very few studies that are centred on evaluating ecosystem services by water bodies. Although there are few studies focusing on ecosystem services assessment of surface water [13,17] and groundwater ecosystems [18], it is imperative to have a region-specific list for more detailed study of the ecosystem services within that area. With this motive and with the aim of focusing on ecosystem services assessment of drinking water sources, Gärtner et al. (2022) developed a region-specific list of water system services [6], which helps users in identifying services provided by drinking water sources. In their studies, water system

services (WSS) are built on the concept of ES and they define WSS as "the aspects of drinking water sources utilized to produce human well-being".

Water system services list is derived from CICES list. WSS list follows the same hierarchy as CICES list with sections (provisioning, regulating, and cultural services), division, group, class, examples, clauses (*Table 1*) and the list provides a list of ecosystem services specially tailored to drinking water systems (water system services) with fewer service classes, groups, and divisions. Only relevant service classes are included in the list of services. For instance, the marine ecosystem service class and rainwater service class are not included as they are do not directly fall under drinking water sources. Furthermore, abiotic and biotic classes are merged if they have similarities. For example, pest control incl. invasive species and disease control services are merged as they offer similar services. *Table 1* shows an excerpt of provisioning service from the WSS list which is similar to CICES list except 'Water clause' is used instead of 'Ecological clause' as WSS list is tailored specifically to drinking water sources [6].

Table 1. Excerpt of provisioning service from the WSS list.

Section	Division	Group	Code used in CICES v 5.1	Class	Examples of Services	Water clause	Use clause
Provisioning service	Biomass (aquatic)	Food	1.1.2.1, 1.1.4.1	Cultivated plants or animals	- Crayfish, char, eel, rainbow trout, steel head trout, salmon	Nature's contribution to the growth of organisms in aquaculture	...that can be harvested and used as raw material for the production of food

While other ecosystem services frameworks such as CICES, MEA and TEEB encompass on border range of ecosystem services, the WSS-list is more focused on services related to water sources used for drinking water supply. Additionally, the WSS-list includes more detailed and specific services related to drinking water sources which are not included in other frameworks.

2.4   Risk management

The overall aim of risk management is to assess, monitor, review, record, and report potential risks that could have negative impact on a project/organization. It is an iterative process which includes Risk analysis, Risk evaluation and Risk reduction/control [19]. *Figure 1* represents the structure of the risk management process as described by International Electrotechnical Commission (IEC). However, the structure and content of risk management process may vary with the objective of different process/projects.
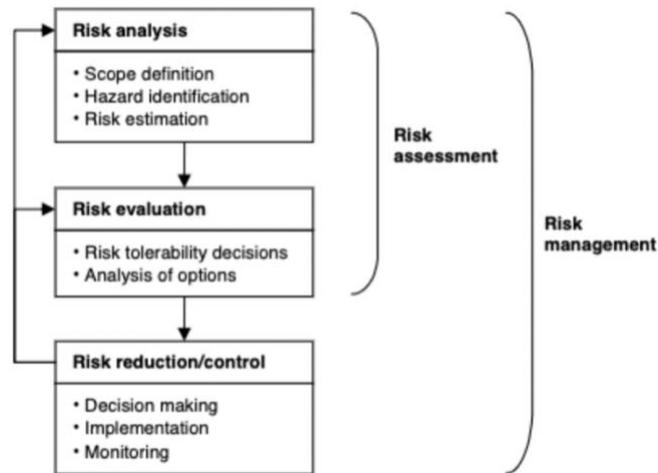
Figure 1. Outline of Risk management. (IEC, 1995)

Risk analysis is the first step in risk management. Scope of the project is defined as the first step of the risk analysis and then the hazards are identified, and risk is estimated. The second step of the project is *Risk evaluation,* in which the risks are evaluated to decide if the risk is acceptable or unacceptable. Acceptable risks are dropped and will not be considered further but need to be monitored for future consequences. Unacceptable risks will be evaluated, and alternatives for how to reduce the risk will be decided in the third and final step of the risk management, which is *Risk reduction/control*. The final step of the risk management includes decision making, implementation and monitoring of the implemented measures. In general, risk management helps identify and manage risks in systematic and structured manner. This study focuses primarily on risk assessment. Risk reduction measures are not designed or monitored as part of this study but are suggested within the results section of the study based on the results of the risk assessment.

Risk assessment is a part of the risk management process which involves *Risk analysis* and *Risk evaluation*. As mentioned earlier, risk analysis involves hazard identification and risk estimation. To understand hazard identification and risk estimation, it is imperative to first understand, what a *hazard* is and what a *risk* is?

A hazard is often defined as a "process, phenomenon or human activity that may cause loss of life, injury, or other health impacts, property damage, social and economic disruption or environmental degradation." [20]. A hazard towards drinking water source can be a hazardous substance which can cause adverse changes in water quality and thus threaten safety of water supply [21,22]. Often, a hazardous substance is defined as a "biological, chemical, physical or radiological agent that has the potential to cause the harms" [19]. Hazardous substances towards drinking water source can be human pathogenic micro-organisms, chemicals, radiological

agents, or physical particles. And the process by which these hazardous substances might be introduced to water bodies is called 'Hazardous event' [22]. Example for hazardous event can be, heavy rainfall, pipe failure, car accidents etc. Hazardous substance can be induced to water bodies by one hazardous event or by combination of several hazardous event or by multiple hazardous event. For example, microorganisms can get into water bodies by human faces which is washed up by heavy rain or it can also reach the water body by failure of sewage network. It is also important to note that there are other types of hazards or activities associated with drinking water supply, such as a lack of water supply, which implies that not only water quality but also water quantity is considered as a hazard. Depending on how often and how severe the hazardous event is, probability and consequence can be assessed to determine the risk.

During risk analysis process, it is important to identify potential hazards. Hazard identification is "the process of recognizing that the hazard exists and defining its character" [19], which in this study is identifying and mapping the hazards within the groundwater and surface water catchment area. As mentioned earlier type of hazards vary with the scope of the study. For example, the hazards concerning the workplace might not be same with the hazards concerning the chemical industry. Hence, different hazard identification database has been developed. In this study the TECHNEAU hazard database is used, as it provides extensive checklist of potential hazards of technical, environmental, and human origin for the entire drinking water supply systems [23].

Risk can be defined as "the likelihood of identified hazards causing harm in exposed populations in a specified timeframe, including the magnitude of that harm and/or the consequences." [23]. Characterizing the risk is the first step in risk estimation, which involves assessment of likelihood, evaluation of consequence, and then determining the risk level for identified potential hazards. A detailed process of risk estimation and evaluation along with the formulas used is explained in the later part of the study.

3 Case Study Sites

In this chapter, the case study sites are introduced. The location, hydrology, hydrogeology, geology, geography of both the case study sites are described in this section. There is also a description of laws/guideline for drinking water protection with respect to both the case study sites. The main findings from other studies on the case study sites are also presented within this section.

3.1 Bohal Spring (GW source)

Bohal Spring is located at an elevation of 1648m at the foothills of Dhauladhar range in Western Himalaya [24] (*Figure 2*). Administratively it falls under Palampur Municipal Council (PMC) which comes under Kangra district in Himachal Pradesh, India. It is used as a major drinking water source for Palampur town which is located downstream and the surrounding Bohal village. The average temperature around the study site is about 17ºC. Bohal Spring is trapped through a spring box and pipeline network (*Figure 2*), and it discharges at a rate of 235 lpm [24]. The quality of the water fulfills the quality standards of Indian drinking water standards.
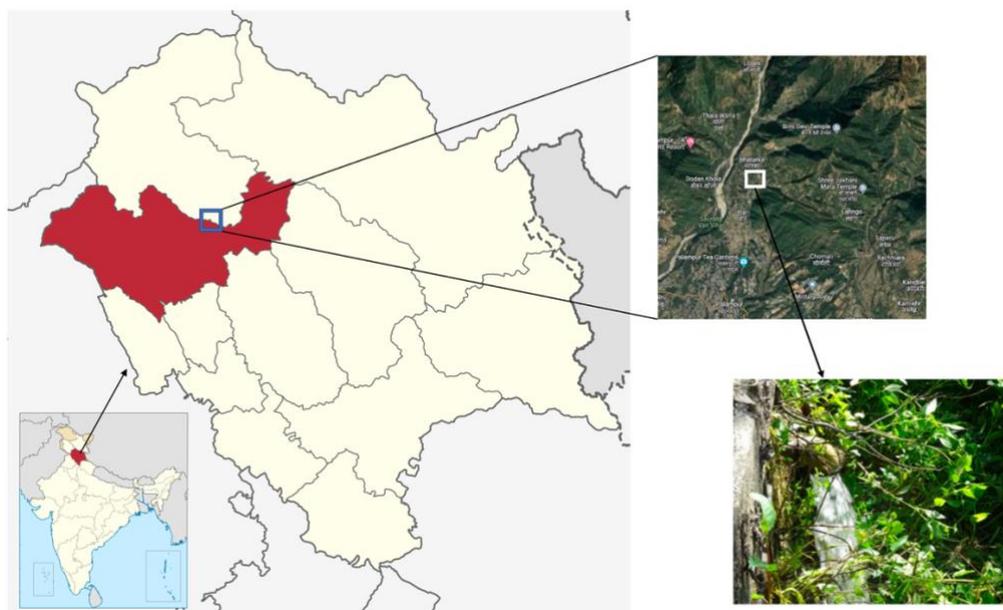
Figure 2. Location of Bohal spring. It is located at the foothills of Dhauladhar range. (Image source - Extracted (from 25, 24, and google map) and modified. Location of Bohal spring is not to precession)

The Bohal Spring is categorized as depression spring and the geology of Bohal catchment is characterized by loose unconsolidated fragments like gravel, boulders and cobblers which are deposited over phyllites [24]. In the studies by Neha Bhavi et al. [24], they presented the detailed hydrogeology of the case study site which is presented in *Figure 3*. *Figure 3* shows the recharge area for the Bohal Spring and the location of the of the 2 fracture zones near the Bohal

Spring which are dipping at 130-310º and 30-210º. Topographical slope is around 25-50% and the region is prone to soil erosion [24].
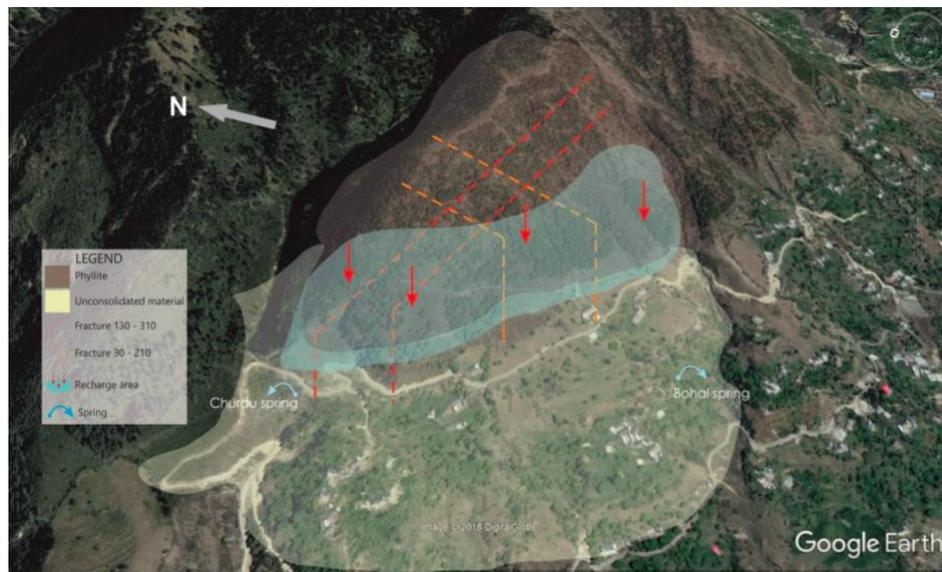
Figure 3. Recharge area and hydrogeology of Bohal catchment. (Image source - 24)

To manage the Bohal catchment area, a 20-year forest management plan was drafted under Palampur Water Governance Initiative (PWGI) in 2009-10 with the Bohal-Odi Village Forest Development Society [26]. Under this initiative, a payment for ecosystem service (PES) model is followed by Palampur Municipal Council (PMC), where they pay 10,000 Rupee annually to the villagers surrounding the Bohal Spring to maintain the Bohal catchment area against grazing, indiscriminate lopping etc. Furthermore, there is complete ban on extraction in the Bohal spring recharge zone and certain part of the recharge zone is classifies as 'Protected forest' to ensure that long term drinking water is provided to the stakeholders [26].

Bohal Spring was selected as a case study site for groundwater ecosystem assessment as payment for ecosystem services (PES) model has been implemented in the spring shed area and there is good data availability. Furthermore, there has been studies accounting the ecosystem services from Bohal Spring shed area using TEEB's ES-framework [**Error! Reference source not found.**], which can be used as a reference to compare with WSS's ES-framework.

3.2 The Dal Lake (SW source)

The Dal Lake is in Srinagar city of Jammu and Kashmir, which lies between 34°18'N to 74°91E at a mean altitude of 1583 m above mean sea level [27] (*Figure 4*). It falls under state government of Jammu and Kashmir and is maintained by Lakes and Waterways Development Authority (LAWDA), government of Jammu & Kashmir. It is called "Jewel in the crown" due to its magnificent beauty and is the major tourist attraction in Srinagar city (*Figure 5*). The lake is used

for commercial fishing, vegetable harvesting and as a source of drinking water (about 170.34 million liters per day) [28].
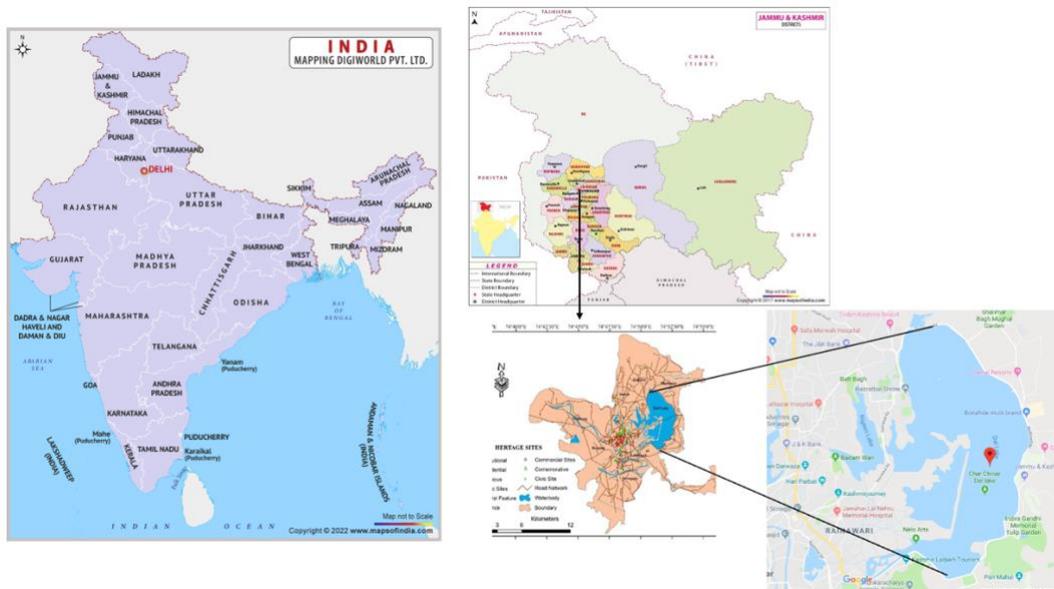
Figure 4. Location of the Dal Lake. It is located in Srinagar city of Jammu and Kashmir. (Image source - extracted from 29, 30, 31, & 32)

Figure 5. Scenic view of Dal Lake with house boats and mountains. (Image source - 33)

The Dal Lake is the second largest lake in Jammu and Kashmir with an area of about 24 km^2 which comprises of 4 basins namely Hazratbal basin, Nishat basin, Gagrabal basin and Nigeen basin (*Figure 6*).
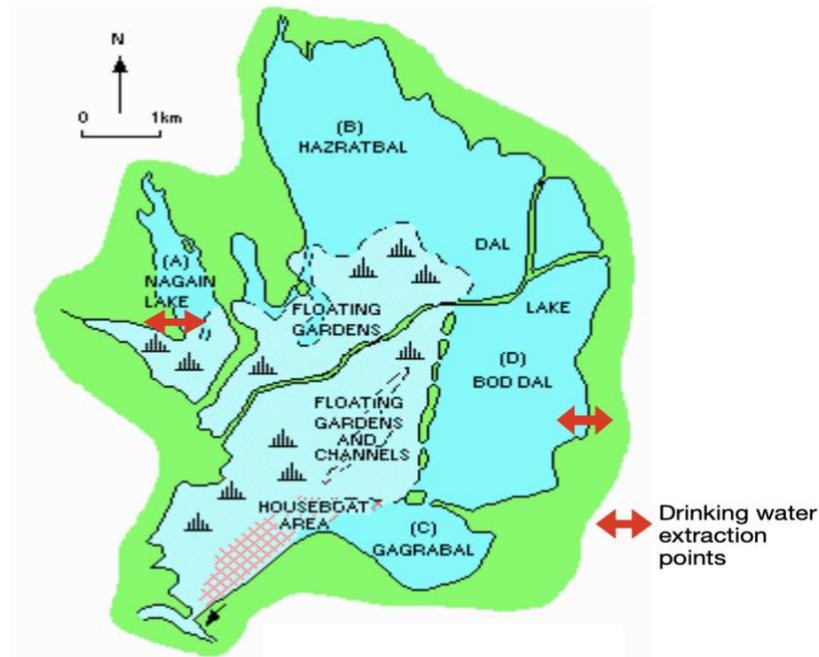
Not to scale

Figure 6. Schematic map of the Dal Lake showing locations of DW extraction points and 4 basins. (Image source: Extracted and modified from World Lake database [27], approximate location of DW extraction point have been added by the author.)

Historical theories suggest that the lake was formed in Pleistocene period from a post-glacial lake [34]. The Dal Lake has varied topography and is spread over an area of 333km^2. Telbal-Dachigam is the largest sub-water shed (~230km^2) from the north through which contributes to about 60-70% of the lakes' inflow [35]. Boutkol, Telbal, Pishpaw and Meerakshah are the other small creeks which feeds the lake along with some contributions from groundwater [36]. It is a multi-basin lake with two outlets Dalgate and Amir Khan Nallah which connects River Jhelum and Anchar lake respectively [37].

Although there are no special laws enforced especially for drinking water protection purpose, there are other legislative and institutional measures enforced to protect the lake environment in general. "Save Dal Project" was launched in 1997, under which 500 crore rupee (~ 5,54,07543 EUR) was sanctioned to save the lake [38]. Lake and Waterways Development Authority (LAWDA) and the State Disaster Response Force (SDRF) are working together to keeps the weeds in check under this mission. Under "Conservation and Management of Dal" program restoration and rehabilitation programs are implemented at various phases by Government of India's National Lake conservation plan [38]. The government of Jammu and Kashmir has also imposed fine and imprisonment policy for any activities which leads to pollution of the lake. Along with these laws there are many other NGO's and independent organizations working in order to protect the Dal Lake from anthropogenic activities.

Despite all the laws and measures the quality of the lake is still degrading day to day. The lake is of significant importance to Srinagar city and thus it is important to map the ecosystem services the lake provides. It is also important to carry out a risk assessment. Being in the heart of the city, there are many studies on the Dal Lake focusing on different aspects which provides good amount of data required for this study. Therefore, the Dal Lake was chosen as a case study site for the surface water assessment.

4 Methodology

This chapter gives an overview of the methods used to carry out the Water System Service assessment, and to identify the hazards associated with the study sites. It also presents how the risk assessment was performed.

4.1 Water system service assessment

The WSS-list is used to identify services of both the case study sites. The complete Water System Service (WSS) list is presented in Appendix A (*Table AA1, AA2, AA3*).

The ecosystem services are identified from various data sources as listed in *Table 2*. Identified ecosystem service is checked off the list by providing at least one example with respect to each case study site. These examples are first verified with CICES's example list, to ensure that all ecosystem services are included. The service classes are excluded if there are no relevant examples available with respect to the case study sites.

Table 2. List of data sources used to identify WSS.

Sl. no	List of data sources
1.	Research papers
2.	Articles
3.	Technical papers
4.	Media reports
5.	Google images

4.2 Risk assessment based on water system services

Integration of water system services into risk assessment is done in three steps. The first step is identifying and characterizing the hazard/hazardous event which is important for risk analysis. The next step is risk estimation, where the risk posed by each hazard is estimated. The last step is evaluation of the water protection measure to mitigate the risks.

In the hazard identification, only the hazards related to the water sources are identified. A checklist is used to identify the hazards. Based on the scope of the study qualitative analysis is carried out. The same procedure is implied for both the case study sites.

4.2.1 Hazard identification

For identifying hazards, the TECHNEAU hazard database was used. TECHNEAU hazard database is a tool used to identify potential hazards associated with water supply systems, it has 12 sub-systems [39]. In this study, 4 sub-systems were used: 1. Surface water catchment, 2.

Surface water intake and transport, 3. Ground water catchment, and 4. Ground water abstraction and transport.

Hazards relevant to the case study sites are checked off the TECHNEAU database list. The data sources used for hazard identification are same as the ones used for WSS assessment (see *Table 2*). The list contains description of hazard sources and specific threat from hazardous event, if any. The definitions of the different types of hazards and consequence to sub-systems is mentioned in *Table 3*. All types of hazards associated with the water supply mentioned in *Table 3* are being considered in hazard identification process.

Table 3. Definitions of type of hazard and consequence to sub-system applied in TECHNEAU data base.

Type of Hazard:	*Biolog.: biological*
	Chemic.: chemical
	Rad./ phys.: radiological or physical (including turbidity)
	Unavail.: insufficient availability of water supplied to customers
	Safety: safety to personnel
	External damage: external damage to third parties, including liability
Consequence to sub-system:	*Description of potential consequences of the hazard to other sub-systems at firstly and the consumer secondly.*

The hazard identification is an iterative process; the entire process should be repeated with any newly identified hazards in the future. The entire process was conducted remotely as both the case study sites are in India.

4.2.2 Risk estimation

The World Health Organization (WHO) promotes a risk-based approach as the most protective means of ensuring acceptable drinking water supply to end users [23]. This includes understanding the scope, prioritizing the risks, ensuring the approximate risk reducing measures are taken to control the risks. WHO suggests calculating risk priority score for each identified hazard as part of a Water Safety Plan [15].

There are several ways to calculate the risk priority scores. In this study the risk (R) posed by hazard (i) on a water system service (WSS) (j) is calculated by the equation 1 [6].

$$R_{ij} = l_i \cdot v_i \cdot c_{ji} \qquad\qquad (1)$$

where l_i is the likelihood of the hazard source (i) causing potential threat to water source, v_i is the vulnerability of the water source to respective hazards i, c_{ji} is the consequence severity to WSS j from the hazard i. The likelihood (l) and vulnerability (v) are considered independent of

WSS, and thus only one l and v scoring for each hazard. The variables likelihood (l) and vulnerability (v) were score from 1-5, while the variable consequence severity (c) was scored from 1-5. The descriptions of the likelihood (l), vulnerability (v) and consequence severity (c) were adopted from the study by Gärtner et.al (2022) which were initially adopted from WHO's Water Safety Plan manual [23] and is explained in detail in *Table 4*.

Table 4. Description and respective score values of the values of the variables likelihood (l), vulnerability (v), and consequence severity (c). (Reference – 6, 23)

	Variable	Score	Description
Likelihood (l)	Most unlikely	1	Very uncommon event - probably will never occur
	Unlikely	2	The event may not occur
	Foreseeable	3	The event could occur
	Likely	4	The event has happened before and can probably occur again
	Almost certain	5	A very common event, occurs regularly
Vulnerability (v)	Insignificant	1	Water source is barely vulnerable to a hazardous event
	Low	2	The water source has a very good ability to withstand the effects of the hazardous event
	Moderate	3	The water source has a good ability to withstand the effects of the hazardous event
	High	4	The water source has very little ability to withstand the effects of the hazardous event
	Extreme	5	The water source cannot withstand the effects of the hazardous event
Consequence severity (c)	No consequences	0	WSS will in no manner be affected if the hazardous event occurs
	Insignificant	1	Insignificant potential to cause harm to WSS
	Minor	2	Potential to cause minor discomfort to WSS
	Moderate	3	Potential to cause a moderate impact on WSS (no long-term consequences)
	Major	4	Potential to cause a major negative impact on WSS (incl. long-term consequences)
	Catastrophic	5	Potential to cause a catastrophic negative impact on WSS (incl. long-term consequences)

The total risk from the hazard (R_i) is calculated by the sum of risk by hazard (i) on all the WSS (m), as

$$R_i = \sum_{j=1}^{m} R_{ij} = \sum_{j=1}^{m} l_i \cdot v_i \cdot c_{ji} \qquad (2)$$

Also the total risk posed by a WSS (R_j) is calculated by summation of all the hazards (n) a WSS (j) is exposed to, as

$$R_j = \sum_{i=1}^{n} R_{ij} = \sum_{i=1}^{n} l_i \cdot v_i \cdot c_{ji} \qquad (3)$$

To have an overview of percentage contribution of total risk from the hazard R_i. Sum of risk by hazard (i) on all WSS (m) is divided by total sum of all the hazard (n) on all the WSS (m), as

$$\% \text{ Contribution to overall risk} = \frac{\sum_{j=1}^{m} R_{ij}}{\sum_{i=1}^{m,n} R_{ij}} \qquad (4)$$

As the last step of risk estimation, risk is divided into 4 categories in order to facilitate the identification of the hazards (i) which pose high risk to WSS (j) (i.e, R_{ij}, risk posed by a hazard i on a WSS j) and to evaluate risk priority score. The risk categories are shown in *Figure 7*.

No risk:	0	Low risk:	1 - 40	Medium to high risk:	41 - 100	Extremely high risk:	> 100

Figure 7. The risk categories with limits and colour coordinate.

The process of risk estimation is same for both the case study sites with respective hazards and WSS.

4.2.3 Water protective measures for risk reduction

In section 4.2.2, we identify the potential source of harm and estimated the risk they pose. This provides a basis for identifying appropriate water protective measures to reduce the risk to different water system services. For example, eutrophication in the lake is caused by many factors like sewage overflow, overfishing etc. Risk estimation helps in calculating the risk scores for sewage overflow and overfishing. Based on the highest risk score, protective measures such as installation of barriers and/or implementation of stricter regulations for fishing can be implemented to minimize the risk. In addition, as already mentioned, generally in India the end-of-pipe approach is used to treat the water, which is not effective. So, risk estimation also helps in identifying risks at all stages of the waters path.

The hazards (i) causing the overall highest risk (i.e., $\sum_{j=1}^{m} R_{ij}$) or the hazards posing the highest risk to one or a selected number of services is identified in section 4.2.2. The WSS with the highest $\sum_{i=1}^{n} R_{ij}$ is also identified in above section (i.e. 4.2.2). Once the most important hazards or services are identified, the effect of water protective measures on the likelihood and consequence and therefore the potential risk reduction can be calculated using equation 5,

$$\Delta R_{ij} = R_{0ij} - R_{kij} \qquad (5)$$

where R_{0ij} is the initial risk before the water protective measures is implemented and R_{kij} is the risk after the water protective measures k (where $k>0$) is assumed to be implemented. The identified water protective measures are reviewed remotely with the data which have been available on the case study sites. The motivation for the implementation of the identified risk reduction measures is presented in the results section.

5 Results

In this chapter, the results of risk assessment based on water system services along with identified water protective measures are presented. Furthermore, a detailed description of the results for the objectives which are mentioned in chapter 1.2 are presented in specific sections as mentioned below. Chapter 5.1 is related to objectives b and c, and chapter 5.2 is related to objectives d, e and f.

5.1 Identified water system services list

The WSS identified for the groundwater source and the surface water sources using the WSS list developed by Gärtner et. al (2022), are presented in sections 5.1.1. and 5.1.2.

5.1.1 WSS list of Bohal Spring – GW source

For the Bohal Spring, totally *eight* services were identified. The services were identified from all the sections, i.e, 4 Provisioning services , 2 Regulating services, and 2 Cultural services. The list of services for the groundwater source with service class and at least one example is presented in *Table 5*. A more detailed list of services along with data source are listed in *Table AA4* in Appendix A.

The water from Bohal Spring fulfils the daily drinking water demand to 907 households, 168 commercial entities and 78 public owners which are located in Palampur Municipal Council [40]. Municipal drinking water (DW) is considered as one of the most important services. Part of the water is stored in a spring box to create a reserve that can be used to supply water to domestic livestock or irrigation.

Table 5. Identified service class with one example each for Bohal Spring (GW source).

	Provisioning Services	**Regulating Services**	**Cultural Services**
Identified Service class with example	Municipal and Private water supply for humans E.g., Municipal DW supply	Prevention of subsidence E.g., Spring helps in maintaining water table level	Scientific investigation, creation of traditional ecological knowledge, education, training E.g., Implementation of PES model in its catchment
	Drinking water for animals E.g., Water used for domestic livestock's	Regulation of local temperature and humidity E.g., Regulates surrounding temperature and humidity	Aesthetic experiences E.g., Looking at the scenic beauty around the spring
	Reserve water source		

E.g., Water is tapped in Spring box		
Water used as a material E.g., Water used in dairy		

5.1.2 WSS list of the Dal Lake – SW source

For the Dal Lake, located in the heart of the city, a large number of water system services were identified. Total *twenty seven* services were identified, 12 Provisioning services, 11 Regulating services and 4 Cultural services. In *Table 6,* the identified services for the Dal Lake are listed with at least one example. A more detailed list of services with description and other examples are presented in *Table AA5* in Appendix A.

A key service from the lake is the '*Municipal DW supply'*, where 170.34 million litres per day (MLD) is drawn from the lake to fulfil the drinking water demand of Srinagar city. Also, the lake is home for a group of shikara riders (people who row the boat) called 'Hanji Community' who use and maintain several services which are listed in *Table 6* e.g., Floating gardens – which are used to produce vegetables are maintained by the shikara riders, they are involved in fishing, they help in transportation within the lake etc. These group of community carry out their living on the lake inside the house boats, hence the service class 'Water used as foundation for floating population' was added to the WSS list. It is added under 'Provisioning Services' in the study, as water is assumed to be material and the material ecosystem outputs people obtain from the nature are thus placed under Provisioning services [11]. The added service class 'Water as foundation for floating population' was searched in all three major ES list, i.e., CICES's ES list, TEEB's ES list and MEA's ES list. It was then added as a service class with suitable description and example from the case study site. A detailed description of section, division, group and class for the added service are listed in *Table AA6* in the Appendix A.

Table 6. Identified service class with one example each for the Dal Lake (SW source).

	Provisioning Services	**Regulating Services**	**Cultural Services**
	Cultivated plants or animals E.g., Vegetable farming	Through dilution E.g., Diluting untreated sewage	Aesthetic experiences E.g., Houseboat stays
	Wild plants or animals E.g., Presence of zoo planktons and algae	Through living processes E.g., Organic elements dumped into the lake	Scientific investigation, creation of traditional ecological knowledge, education, training E.g., Investigations on macrophytes
	Fibers and other materials from cultivated plants or animals E.g., Trees which are used as timber	Through filtration E.g., Purification of air by floating gardens and forest cover	Activities Promoting health, recuperation or enjoyment through active, immersive, passive or observational interactions. E.g., Swimming etc.
	Fibers and other materials from wild plants or animals E.g., Weeds used as compost	Through sequestration E.g., Azollo sp (macrophytes) helps in CO_2 sequestration	Religious, sacred, or symbolic meaning E.g., Presence of lotus plants
	Cultivated plants or animals as an energy source	Through storage or accumulation	

Identified Service class with example	E.g., Trees used as fuel wood	E.g., Plastic and metal waste is dumped into the lake	
	Wild plants or animals as an energy source E.g., Macrophytes has potential biofuel production capacity	Flood Protection E.g., Excess water of Jhelum River flows into the Dal Lake	
	Municipal and private water supply, for humans E.g., Municipal DW supply	Pollination and spreading of seeds by water E.g., Some red algae reproduce by spores	
	Drinking water for animals E.g., Domestic animals DW supply	Fire protection E.g., Presence of wetlands	
	Irrigation E.g., Irrigation for farms	Maintaining Populations and habitats E.g., Potential gene pool conservation	
	Water source as a material E.g., Washing clothes	Controlling the chemical quality of freshwater E.g., Presence of macrophytes	
	Water as a mean for transportation E.g., Shikra riders use boats for local transport	Regulation of local temperature and humidity E.g., Regulates temperature	
	Water used as foundation for floating population E.g., People living on houseboats		

5.2 Risk assessment

The first step in the risk assessment is the hazard identification, which is presented in section 5.2.1. In the next step the identified hazards are scored against each WSS to obtain a risk priority score, which is presented in section 5.2.2. In section 5.2.3, the resulting risk priority score after implementation of water protection measures are presented.

5.2.1 Identified hazards

5.2.1.1 Identified hazards for the Bohal Spring – GW source

Using the TECHNEAU hazard data base, totally *five* hazards were identified in the recharge area contributing to the ground water source. The area of contribution includes the uphill area where the recharge of the spring occurs and the area surrounding the spring where infiltration occurs.

Table 7 presents the list of hazards which were identified for the Bohal Spring source. As seen in *Table 7*, the major contribution to the hazard sources is from the anthropogenic activities and a small contribution is from the wildlife activities. Another important observation from *Table 7* is that the hazard source 'Water tank' is both a service as well as a hazard, which implies a service which is useful for the mankind can also be a hazard source. Furthermore, the hazards identified are also based on future consequences e.g, the hazard source 'Water tank' does not

pose any risk in the present scenario, but can provoke risk if there is any breakage to the structure or due to repair works in the future.

Table 7. Identifies hazard sources for Bohal spring source with hazardous event description.

Hazardous event	Hazard sources	TECHNEAU – database reference no.
Leaching of contamination by **built constructions**	Water tank	2.1.3
Agriculture runoff and leach-out containing fertilizers, sludge, herbicides, etc.	Chemical fertilizers and pesticides used in agriculture fields	2.1.7
Manure spread or cattle in the zone	Livestock grazing in the zone	2.1.8
Contamination by **forestry activities, wild life activities, natural fowls, dead animals,** bird pest (flu)…	Wild life activities, bird pest, leaf litter and natural fowls	2.2.11
Groundwater **aquifer** is **not sufficiently fed** or **water is abstracted** by others	Not sufficiently fed due to overgrazing, leaf fodder extraction	2.1.13

A more detailed description of hazards with data source, specific threat and potential consequences is presented in *Table BB1* in the Appendix B.

5.2.1.2   Identified hazards for the Dal Lake – SW source

The Dal Lake can be said to be in the centre of anthropogenic activities as it is located in the heart of the city. From the area of contribution for the Dal Lake, totally *fourteen* hazards were identified from the TECHNEAU hazard data base. This area includes the catchment of the lake, the surface area of the lake and the area along the periphery of the lake. An area up to 500m along the periphery of the lake was considered.

Table 8 presents the list of hazards which were identified for the Dal Lake. As seen in *Table 8*, most of the hazards are associated with human activities and a little contribution is from the natural phenomena (e.g. silt and sedimentation deposition). Like the Bohal Spring source, the Dal Lake also has many hazards which are caused by water system services e.g., *Latrine deposit* from the houseboat is caused by the humans when utilizing WSS 'Water used as foundation for floating population'.

All the hazard sources listed for the Dal Lake are for the present situation. No assumption is made for the future scenarios as it was difficult to anticipate the future hazards sources due to the location of the Dal Lake. But the list has to be updated for future studies on the site.

Table 8. Identified hazard sources for the Dal Lake with hazardous event description.

Hazardous Event	Hazard sources	TECHNEAU database reference no.
Industrial discharge of biological matter	Discharge from sewage treatment plants	1.1.1
Emissions during accidents (fire or explosions) e.g. industrial accidents or **forest fire**	Emission during accidents	1.1.3
Traffic accidents with ships, trains, vehicles and planes	Road accidents and houseboat accidents	1.1.4
Toxic chemicals from air deposits or **air pollution**	Air pollution from STP's and vehicle exhausts	1.1.5
Emissions and leakage, oil spills (MTBE) by shipping or traffic	House boats fuel leakage, oil from cleaning companies	1.1.7
Latrines deposits from **boats,** etc.	House boats domestic waste	1.1.9
Intensive **fishery**, fish farming, massive fish death	Unregular fishing and massive fish death	1.1.10
Sewer overflows due to rainfalls or failures	Sewer overflows due to lack of efficiency	1.1.12
Erosion into catchment with release of soil, sand or contaminants	Silt and sedimentation deposition	1.1.14
Disposal of **manure**	Manure usage in floating farm	1.1.19
Runoff from **agriculture** and **urban green** areas containing fertilizers, sludge, herbicides, etc	Agriculture runoff	1.1.20
Discharge of **treated wastewater**	Discharge of treated wastewater from STP's	1.1.22
Birds droppings or animals allowed to cross a protection zone	Bird dropping and animal waste	1.1.25
Algae blooms (mostly during summer month's)	Use of fertilizers and pesticides	1.1.26

A detailed description of hazard sources with data source and specific threat is listed in *Table BB2* in Appendix B.

5.2.2   Risk estimation

5.2.2.1   Risk assessment matrix for the Bohal Spring

The outcome of the risk assessment of the hazards of Bohal Spring's WSS is presented in the form of a risk assessment matrix (see *Figure 8*). The complete description of likelihood (*l*), vulnerability (*v*) and consequence (*c*) scoring for all the hazards are presented in *Table CC1* in Appendix C. *The total risk a WSS is exposed to* and *the total risk posed by the hazard to all the services* were calculated using the methods described in chapter 4.2.2 (*Equations 2 & 3*).

Hazard sources	Provisional Services				Regulating Services		Cultural Services		Sum
	Municipal DW supply	DW for animals	Reserve water source	Water used as a material for dairy	Prevention of subsidence	Springs regulating local temperature and humidity	Scientific investigation, education and training	Looking at the springs and surrounding nature	
Water tank and Pipe installations for Handling	40	40	20	10	0	0	0	20	130
Agriculture Runoff	80	80	80	60	0	0	40	40	380
Manure	36	36	36	24	0	0	24	24	180
Forest activities	27	27	27	27	0	0	18	18	144
Less recharge	64	64	48	48	64	48	32	32	400
Total risk a WSS is exposed to	247	247	211	169	64	48	114	134	1234

Contribution to overall risk: 10.53%, 30.79%, 14.59%, 11.67%, 32.41%

No risk:	0	Low risk:	1 - 40	Medium to high risk:	41 - 100	Extremely high risk:	> 100

Figure 8. Risk assessment matrix corresponding the hazard sources and their impacts on WSS for Bohal spring source. Contribution of each hazard source to overall risk is represented by the bar chart on right.

The hazard source *Less recharge* contributes most to the overall risk score, followed by the hazard source *Agriculture runoff*. The hazard source *Less recharge* has highest contribution, as the water quantity is an important factor to deliver all the water system services in case of the Bohal Spring. As mentioned by Uniyal et al. [40], a PES model is implemented in the recharge area to mitigate this hazard source, but the results from the PES model is not considered while calculating the risk score of the hazard source on the water system services. The total risk score will be reduced if the results are considered.

The services *Municipal DW supply* and *DW for animals* has the highest total risk scores compared to the other services, followed by the service *Reserve water source*. Whereas the service *Prevention of subsidence* and *Springs regulating local temperature and humidity* has the least risk score from all the hazards, as they are not affected by the quality of the water and the service is delivered even though the water quality is deteriorated.

5.2.2.2   Risk assessment matrix for the Dal Lake

Figure 9 contrasts the risk assessment matrix of the Dal Lake which corresponds to the hazard sources and their impacts on water system services. The same procedure of risk calculations mentioned in the section 5.2.2.1. were followed for the Dal Lake's total risk calculations. A detailed list (*Table CC2*) of hazard with description of specific threats from the hazards is listed in Appendix B. The list also contains descriptions for the variables *l*, *v* and *c* for each hazard with respect to WSS.

The hazard source *Traffic accidents with vehicles and boat accidents* has the highest score for *the total risk posed by the hazard to all the services,* followed by the hazard source *Intensive fishery and massive fish death.* The hazard source *Intensive fishery and massive fish death* is combination

of 2 hazard sources. As this hazard source is ranked the second highest, both the hazards were separated and the risks were calculated. The results from this separation were the same, as the hazard source *Intensive fishery* affected only one WSS i.e., *Maintaining populations and habitats,* so they were together considered as single hazard source. All the hazard sources except one hazard source (i.e., silt deposition due to erosion) affect the quantity of the water. Which implies that the water of the Dal lake is over exploited due to anthropogenic activities. The calculations are done without considering any water protective laws or measures which are already at enforce in the Dal Lake area.

Like the Bohal Spring, the Dal lake also has the services *Municipal DW supply* and *Drinking water for Domestic animals* the highest risk scores from all the hazard sources among other services. And the service *Mediation of toxic substances and nuisance through accumulation* the least risk score.

Legend:

Category	Range
No risk	0
Low risk	1 - 40
Medium to high risk	41 - 100
Extremely high risk	> 100

Hazard sources	Total risk a WSS is exposed to	Algae Blooms	Bird droppings and Animal waste	Discharge of treated wastewater	Fertilizers and herbicides runoff from agriculture	Disposal of manure	Silt Deposition due to erosion	Sewage overflow	Intensive fishery and massive fish death	Latrines deposits from boats	Oil spills from car company and road accidents and leakage from house boats	Toxic chemicals from air deposits	Traffic accidents with vehicles and boats	Emissions during Boat accidents	Industrial discharge of biological matter	
Cultivated plants as food	623	60	10	30	45	24	40	60	48	45	60	45	80	16	60	Provisional Services
Wild plants as food	591	48	10	30	45	24	40	60	48	45	60	45	60	16	60	
Timber from cultivated plants	396	36	10	10	30	16	40	30	48	0	45	30	40	16	45	
Fibres and other materials from wild plants	614	48	20	30	45	32	40	60	48	30	60	45	80	16	60	
Cultivated plants as fuel wood	411	36	10	10	30	16	40	30	48	30	30	30	40	16	45	
Wild plants for biofuel production	334	0	10	0	0	0	40	0	48	45	45	30	40	16	60	
Municipal DW supply	731	48	40	30	60	40	40	60	64	60	75	45	100	24	45	
Drinking water for Domestic animals	777	48	40	30	60	40	40	75	80	60	75	45	100	24	60	
Irrigation	506	36	10	20	30	16	40	30	48	30	45	45	80	16	60	
Water used for washing clothes	391	12	10	30	30	16	20	45	48	30	45	15	60	0	30	
Water for local transportation within the lake	292	24	10	20	30	16	0	30	32	30	30	0	40	0	30	
Water used as foundation for floating population	361	12	10	20	30	16	40	30	32	30	30	45	20	16	30	
Mediation of waste through living processes	493	48	10	30	30	16	40	45	48	45	45	30	60	16	30	Regulating Services
Mediation of waste, toxic substances and nuisances through dilution	332	36	10	0	30	8	40	30	48	30	30	0	40	0	30	
Mediation of waste, toxic substances and nuisances through filtration	503	36	10	30	45	24	40	45	48	45	45	30	60	0	45	
Mediation of waste through sequestration	459	36	10	10	45	24	0	45	48	45	45	30	60	16	45	
Mediation of toxic substances and nuisance through accumulation	72	12	0	0	0	0	60	0	0	0	0	0	0	0	0	
Flood protection	380	36	0	30	45	24	80	45	0	45	30	0	0	0	45	
Fire protection	190	24	0	20	30	16	40	30	0	30	0	0	0	0	0	
Spreading of seeds by red algae	295	24	10	30	15	0	0	30	32	0	30	30	40	24	30	
Maintaining populations and habitats	608	48	10	40	45	24	40	60	80	45	45	30	80	16	45	
Maintaining water quality (chemical quality)	464	36	10	30	45	24	0	30	48	45	45	30	60	16	45	
Regulation of local temperature and humidity	234	36	0	30	30	16	0	30	32	30	0	0	0	0	30	
Physical and experimental interactions with natural environment (Swimming,	491	36	20	30	30	16	40	45	48	45	45	30	60	16	30	Cultural Services
Scientific investigations inside and around the lake	378	60	20	20	30	16	40	30	32	30	30	0	40	0	30	
House boat stay to experience nature	388	24	20	20	30	16	40	30	32	30	30	30	40	16	30	
Sacred presence of Lotus plants	471	48	10	30	45	24	40	45	48	30	45	30	60	16	0	
Sum	11785	948	330	610	930	504	920	1050	1136	930	1065	690	1340	312	1020	

Figure 9. Risk assessment matrix corresponding the hazard sources and their impacts on WSS for the Dal Lake.
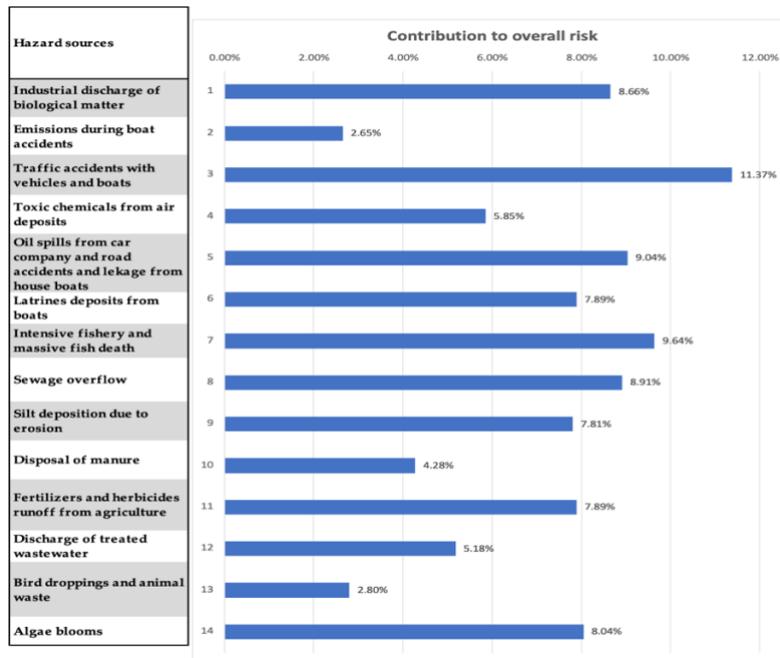
Figure 10. The bar chart indicating contribution of each hazard source to overall risk.

5.3 Risk reduction / control

In this section, possible water protection measures that can be used to reduce or control the existing risks associated with Bohal spring and Dal lake water sources are presented and evaluated.

5.3.1 Water protective measures

The hazards which has the highest risk score and the services exposed to most of the hazards were identified in section 5.2.1. Water protective measure can be implemented to any one of these or both of these, i.e., the focus can be to mitigate the hazard with highest risk score or to protect the service which is important. Even though the focus of this study is on drinking water, the hazard source which posed highest risk to all the WSS were given importance to evaluate the water protective measures. This helps in analysing the effectiveness of water protective measures and to see the relationship between the hazard sources and the water system services. All the water protective measures were identified through brainstorming.

5.3.1.1 *W*ater protective measures identified for the Bohal Spring

For the Bohal Spring, hazard sources *Less recharge* and *Agriculture runoff* posed high risk to majority of the water system services. *Figure 11* shows the water protective measures which were identified for these two hazards.

For the hazard source *Less recharge,* 3 water protective measures were identified as shown in *Figure 11*. The hazard source *Less recharge* is associated with reduced recharge due to extensive fodder extraction and over exploitation on the vegetation cover from livestock grazing activity. This hazard source can be mitigated by (a) imposing rules on fodder extraction and livestock grazing in the zone of recharge or (b) by pumping the water externally to maintain the ground water table. The final selection of the most suitable water protective measures depends on the decision makers' aim and objectives as well as available financial and other resources. But both the water protective measures reduces the risk score as seen in *Figure 11*. The total risk is reduced by 62.5% (250/400) after implementing risk reducing measures, which is less than half of the original risk score.

Also, for the hazard source *Agriculture runoff* , 3 water protective measures were identified (see *Figure 11*). The main risk from the *Agriculture runoff* is that there is a possibility that the chemicals and fertilizers flow out of the agriculture area or gets infiltrated into the groundwater. This hazard can be mitigated by practicing crop rotation so that the soil is rotated adequately and the soil health is maintained. The other possible way is by digging trenches around the agriculture field or by planting trees/shrubs along the periphery of the agriculture field boundary, so that no soil is washed off the field and stays inside the boundary. Implementing these water protective measures for the hazard source *Agriculture runoff* reduced the risk score by 60% (228/380), which is also less than half of the original risk score (see *Figure 11*).

As there are numerous other water protective measures which can be implemented, care should be taking in evaluating all the water protective measures by their practical applications and by evaluating the socio-economic aspects of the stakeholders with respect to the aim of the project.

Hazards	Water protective measures						
Less recharge	· Restricting livestock grazing in recharge zone	Description	Foreseeable	The water source has very good ability to withstand the effect of hazardous event	Total risk, before implimenting risk reducing measures	Total risk, after implimenting risk reducing measures	Percentage risk reduction (%)
	· Pumping water to maintain water table level from nearest river	Score	3	2			
	·Limiting the fodder extraction		Risk posed by a hazard towards a WSS Risk = l · v ·c		400	150	62.5
Agriculture runoff	·Application of Agriculture Management Practices	Description	Unlikely	No protective soil layer; slow contaminant degradation	Total risk, before implimenting risk reducing measures	Total risk, after implimenting risk reducing measures	Percentage risk reduction
	· Digging trench around the boundary	Score	2	4			
	· By planting field buffers (i.e. planting shurbs and trees along the boundary)		Risk posed by a hazard towards a WSS Risk = l · v ·c		380	152	60

Figure 11. Table showing the effect of water protective measures for the Bohal Spring. The risk reduction is presented for the hazards posing the highest initial risk.

5.3.1.2   *Water protective measures identified for the Dal Lake*

For the Dal Lake, hazard sources *Traffic accidents from vehicles and boats* and *Intensive fishery and massive fish death* has high risk score values. The water protective measures identified for both the hazards are shown in *Figure 12*. The water protective measures identified for *Intensive fishery and massive fish death* also reduced the risk from the hazard source *Sewage overflow*. Therefore the partial risk reduction score is also calculated for the hazard source *Sewage overflow*.

Three risk reducing measures were identified for the hazard source *Traffic accidents from vehicles and boats* as seen in *Figure 12*. The major risk from the traffic accidents is the leakage of oil from the vehicles, which is harmful for living beings. The identified risk reducing measure, *Replacing the old and damaged boats* is concerned with the vehicles within the lake i.e., boats, and other two other measures are concerned with vehicles outside the lake i.e., cars and heavy duty vehicles. By implementing the measure *Replacing the old and damaged boats,* the chances of boat accidents within the lake will be reduced. With the other two options, the movement of heavy duty vehicles will be restricted so that no major accident occurs in the zone of protection and the speed of the vehicles will be reduced which in turn reduces the chances of road accidents. All the three water protective measures together reduces the risk score by 50% (670/1340) of the original risk score values.

Three water protective measures were also identified to the second highest risk scoring hazard source *Intensive fishery and massive fish death*. The major cause for this hazard source is reduced dissolved oxygen (DO) level, which is due to increase is nutrient intake and irregular fishing. This can be mitigated by regulating the fishery permits and; either by restricting the intake of nutrients into the lake or by aerating the lake. The implementation of these measures reduces the risk score by 50% (568/1136) of the original risk score value as seen in *Figure 12*.

As mentioned earlier, implementation of the risk reduction measures for the hazard source *Intensive fishery and massive fish death*, also applies for the hazard source *Sewage overflow*. As seen in *Figure 12* the total risk score of the hazard source *Sewage overflow* is also reduced by 40% (420/1050).

Hazards	Water protective measures				Total Risk, before implimenting Risk reducing measures	Total Risk, after implimeting Risk reducing measures	Percentage risk reduction (%)
Traffic accidents from vehicles and boats	Replacing the old and damaged boats	Description	Unlikely	Cannot withstand the effect of hazardous event; No protective barriers			
	Installing speed breakers and adding speed limits to drive on the roads surrounding the lake	Score		2 5			
	Restricting the movement on heavy duty vehicles on the roads surrounding the lake	Risk posed by a hazard towards a WSS — Risk = l · v ·c					
					1340	670	50
Intensive fishery and massive fish death	Enforcing better regulations for fishery permits	Description	Unlikely	Direct exposure; Very little ability to withstand the effect of Hazardous event	Total Risk, before implimenting Risk reducing measures	Total Risk, after implimeting Risk reducing measures	Percentage risk reduction
	Reducing the nutrient loading to the lake, eg. taking care of untreated waste that enters the lake, treating the sewage before it enters the lake (improving the drainage system)	Score		2 4			
	Aerating the lake artificially to provide sufficient O2.	Risk posed by a hazard towards a WSS — Risk = l · v ·c					
					1136	568	50
Sewage overflow	Improving the drainage system and treating the waste before it reaches lake	Description	Forseeable	Has good ability to withstand the effects of hazardous event in smaller amounts	Total Risk, before implimenting Risk reducing measures	Total Risk, after implimeting Risk reducing measures	Percentage risk reduction
		Score	3	3			
		Risk posed by a hazard towards a WSS — Risk = l · v ·c					
					1050	630	40

Figure 12. Table showing the effect of water protective measures for the Dal Lake. The risk reduction is presented for the hazards posing the highest initial risk.

6   Discussion

The overall aim of this study is to apply the concept of water system services introduced by Gärtner et al.(2022), to two case study sites in India in an attempt to identify how the list may be complemented and adapted to other regions. Additionally, the study aims to integrate the identified water system service list into the a risk assessment for the studied case study sites.

Specific objectives are to:

a) Identify two suitable case study sites in India (one groundwater source and one surface water source).

b) Perform a water system service assessment for the case study sites.

c) Identify missing water system services for the studied sites by cross-checking with CICES.

d) Identify hazards for both the case study sites and perform a risk assessment.

e) Identify and evaluate possible water protective measures.

f) Evaluate the list's applicability to other region besides Sweden for which it was originally developed.

6.1   Insights from WSS list application to case study sites

The overall aim of the study was to integrate the concept of water system services introduced by Gärtner et al. (2022) to two case study sites in India to evaluate the applicability and identify how the list may be complemented and adapted to other regions. The case study applications showed that the WSS list is applicable not only to Swedish region which it was developed for. Hence, the list can be transferred to other case study sites irrespective of their geographical location. For Bohal Spring, no newly discovered ecosystem services were found outside the WSS list. For the Dal Lake, only one unidentified ecosystem service was found outside the WSS list. This clearly demonstrates that the WSS list can be transferred to other case study sites without any modifications. However, the area must be thoroughly examined in order to identify any ecosystem services that may not be included in the WSS list. This is to ensure that all the ecosystem services are identified and can be added to the list. Furthermore, the application of the WSS list can be enhanced by incorporating a wide range of stakeholders in the WSS identification process. By including local communities, policy makers, decision makers, and practitioners, and others, a variety of perspectives can be taken into consideration. For example, decision makers may not understand the region's ecosystem services, while local communities have a deeper understanding of regional ecosystems. It is important to apply the WSS list to more sites to potentially identify more missing services.

The results of the WSS assessments in the case studies indicate that surface water provides more ecosystem services than groundwater. This implies that surface water is more visible and accessible than groundwater which makes it easier for us to access and benefit from. For example, surface water can be used for fishing, recreational purposes etc., while groundwater can't be used for such purposes but can be used as a source of drinking water or to maintain subsidence etc. Even though both play a crucial role in sustaining ecosystems, surface water is more exploited due to its accessibility. Furthermore, groundwater also feed into the surface water sources so it a crucial part of hydrogeological cycle.

As discussed earlier, a major challenge in linking research on ecosystem services to human well-being is lack of data and generalized framework to link ecosystem benefits and human well-being in a cost-effective and time-effective manner [8, 9]. The findings from the WSS assessment indicates that, regardless of geographical location, the WSS list developed by Gärtner et al. (2022) can identify all ecosystem services related to drinking water sources and can be used as a generalized framework to assess ecosystem services linked with drinking water sources.

6.2 On linking WSS list to risk assessment of drinking water

Hazard identification was carried out as a first step when assessing the risk and the results from the hazard identification plays a crucial role. By evaluating the risk the hazards pose, we can ensure the safety of the drinking water provided to the consumer by mitigating the risks from the catchment to the tap and not on end product testing [15]. Hazard identification is done using the TECHNEAU hazard data base, which was very effective in mapping potential hazards or risk that could impact drinking water safety and quality. As the TECHNEAU hazard database is easily accessible and provides a comprehensive coverage of potential hazards, it can be used as an efficient tool to gather information on hazards. It could also be completed within a reasonable timeframe, and it is reasonable to assume to be a cost-effective approach.

With respect to second aim of the study, which was to integrate WSS list into risk assessment of drinking water, the results from the risk assessment matrix shows that the identified WSS list can be effectively integrated into hazards from the source water supply (i.e., surface water and groundwater). The risks estimated by means of the risk assessment matrix supports source water management by enabling an assessment and presentation of the likelihood, vulnerability and consequence of the hazard. The results from the Bohal case study site and the Dal Lake site illustrates that the hazards associated with the highest risk score poses a threat to almost all the ecosystem services and the hazards with the lowest risk only poses a threat to a limited number of services. Also, few services like *Prevention of subsidence* and *Spring regulating local temperature* and *humidity* (for groundwater source)*, Mediation of toxic*

substance and nuisance through accumulation and *Fire protection* (for surface water source) is affected by only few hazards. This shows that the risk assessment matrix provides a visual representation of the risk estimation process and contributes majorly to the decision making process. The results from risk assessment matric can either be used to identify management and mitigation option for each hazard or for each service.

By applying the risk mitigation measures to the hazards with high risk priority scores for the Bohal spring and the Dal Lake, the total risk score was reduced to more than half of the previous scores (60% and 62.5% for the Bohal springs, 50% for the Dal Lake) as mentioned in chapter 5.3.1. Implementation of the risk reducing measures helps in reducing the likelihood and impact of the adverse effects which can affect water sources. In the case of the Dal Lake, the risk mitigation measures for *Intensive fishery and massive fish death* also reduced total risk score of the hazard source *Sewage overflow (by 40%)*. This result illustrates that most of the hazard sources are interlinked with one another and with the proper risk mitigation measure the risk scores of the interlinked hazard sources can be reduced which in turn can reduce the treatment cost of the water.

It should be noted that the risk assessment was carried out based on existing hazards in case study sites. If the case study sites undergo development in future, then the risk assessment matrix should be updated based on a new hazard identification and a new assessment of the likelihood consequence etc.

7 Conclusions and Recommendations

The WSS list provides a clear illustration of the services a water source offers in addition to meeting the drinking water needs of society. By mapping the services, it facilitates the policy makers to incorporate the decisions to protect the ecosystem services which in turn can improve the water quality and accessibility. By integrating the WSS into a risk assessment it is possible to ensure a reliable and sustainable water supply for human beings and the ecosystems. Different priorities affect decision making process, and water protection always has synergies between various stakeholders. It is important to expand the water management process beyond conventional methods by incorporating ecosystem service frameworks like the WSS list as part of developing, for example, water safety plans.

In this study, ecosystem services are only assessed on a regional scale and global benefits such as carbon sequestration, global climate regulation, regulation on the impact of climate change etc., so the services offered cannot be adequately appreciated as they have additional benefits which are not considered in this study. Furthermore, in order to calculate risk scores, all the services were treated equally. This can be improvised by giving different weightage to the services. Another way is to perform a multi-criteria decision analysis (MCDA) which makes it possible to consider different stakeholder perspectives' and include criteria related to environmental, social and economic aspects while scoring hazards. Furthermore, a cost-benefit analysis can be performed for the suggested water protective measures to analyse the costs and benefits of measures to all in society.

8 Appendix

8.1 Appendix A – Water System Service list

Division	Group	Code Used in CICES v 5.1	Class	Examples of Services	Water Clause	Use Clause
Biomass (aquatic)	Food	1.1.2.1, 1.1.4.1	Cultivated plants or animals	- Crayfish, char, eel, rainbow trout, steelhead trout, salmon	Nature's contribution to the growth of organisms in aquaculture …	… that can be harvested and used as raw material for the production of food
		1.1.5.1, 1.1.6.1	Wild plants or animals	- Perch, pike, zander, rainbow trout, char, roe from fish - Watercress	Parts of the standing biomass of non-cultivated aquatic organisms and their outputs …	… that can be harvested and used as raw material for the production of food
	Material	1.1.2.2, 1.1.4.2	Fibers and other materials from cultivated plants or animals	- Jewelry with fish scales as adornment	Nature's contribution to the growth of organisms in aquaculture …	… that can be harvested and used as raw material for non-nutritional purposes
		1.1.5.2, 1.1.6.2	Fibers and other materials from wild plants or animals	- Jewelry with fish scales as adornment - Reed for roofs and crafts or as food for animals	Parts of the standing biomass of non-cultivated aquatic organisms and their outputs …	… that can be harvested and used as raw material for non-nutritional purposes
	Energy	1.1.2.3, 1.1.4.3	Cultivated plants or animals as an energy source	- Reed canary grass for biofuel (fuel pellets) - Biogas from aquaculture waste	Nature's contribution to the growth of organisms in aquaculture …	… that can be harvested and used as a source of energy
		1.1.5.3, 1.1.6.3	Wild plants or animals as an energy source	- Wild reed for heating	Parts of the standing biomass of non-cultivated aquatic organisms and their outputs …	… that can be harvested and used as an energy source
	Genetic Material	1.2.1.1, 1.2.1.2, 1.2.1.3, 1.2.2.1, 1.2.2.2, 1.2.2.3	Genetic material from all organisms	- Wild animals that we can use for breeding - Plants, fungi, or algae that we can use for breeding	Genetic material and information from aquatic organisms …	… that can be used to maintain, develop new varieties or establish a new population, or that can be used in gene synthesis
Water	Water for drinking	4.2.1.1, 4.2.2.1	Water supply for humans	- Municipal water supply - Potable water in the public supply system - Potable water using private wells - Natural springs - Mineral water	Surface water bodies or aquifers …	… that provide a source of drinking water supply for humans

Table AA1. List of Provisioning services from water system service list [6].

Division	Group	Code Used in CICES v 5.1	Class	Examples of Services	Water Clause	Use Clause
	Water for non-drinking purpose	4.2.1.1, 4.2.2.1	Drinking water for animals	- Water source for wild animals - Water source for livestock	Surface water bodies or aquifers …	… that provide a source of drinking water supply for animals
		own description	Reserve water sources	- Potable water system if an existing source cannot be used - Potable water system in the future (e.g., if the demand increases)	Surface water bodies or aquifers …	… that provide a source of reserve drinking water supply
		4.2.1.2, 4.2.2.2	Irrigation	- Land irrigated by controlled flooding - Irrigated temporary grass land, cereals, potatoes, sugar beet, etc.	Surface water bodies or aquifers …	… that provide water which can be used for irrigation
		4.2.1.2, 4.2.2.2	Water used as a material or other type of input into production and consumption	- Water for washing (in industrial processes) - Water for sanitation - Water for mortar - Water used as a transport medium in heating or cooling systems, e.g., in industrial facilities - Water as a material for fire extinguishing	Surface water bodies or aquifers …	… that provide water which can be used as other types of input into production and consumption
	Energy	4.2.1.3	Surface water in hydropower	- Potential and kinetic energy in water that can be used in hydropower to produce electricity	The flow of water on land … .	… that can be converted to electrical or mechanical energy
		4.3.2.5	Geothermal energy	- Hot water and steam from (typically deep boreholes) that can be used for the production of electricity and heating	Hot water and steam from the subsurface of the earth …	… that can be used as an energy source
		own description based on 4.2.2.3	Groundwater and surface water as an energy source	- Groundwater source heat pump - District cooling and heating	Surface water bodies or aquifers …	… that provide water at useful temperatures
		own description	Water as storage of heat and coolness	- Seasonal storage of heat and coolness in aquifers, e.g., heating and cooling of facilities (Arlanda airport)	Surface water bodies or aquifers …	… that provide a source for storage of heat or coolness
	Water for transport	own description	Water as a means of transportation	- Water bodies as a waterway for ships - Frozen surface water bodies as winter ways for vehicles	Surface water bodies or aquifers …	… that provide water which can be used as a mode of transport
Support to other natural systems					Surface water bodies or aquifers forming input to the functioning of other natural systems …	… that provide provisioning services

Table AA1. cont. [6].

Table AA2. List of Regulating services from water system service list [6].

Division	Group	Code Used in CICES v 5.1	Class	Examples of Services	Water Clause	Use Clause
Transformation of biochemical or physical inputs to ecosystems	Mediation of waste, toxic substances, and nuisances	2.1.1.1, 2.1.1.2, 2.1.2.1	Through living processes	- Denitrification - Biofilm in infiltration ponds - Biological degradation of organic substances (petroleum products, chlorinated solvents)	Transformation, fixing, and storage of an organic or inorganic substance, and reducing the impact of odors by aquatic organisms ...	... that mitigate harmful effects or reduce the costs of disposal by other means
		5.1.1.1	Through dilution	- Treated wastewater discharged from a wastewater treatment plant into a surface water body for an effluent dilution	The reduction in the concentration of organic or inorganic substances by mixing in freshwater, ...	... that mitigates harmful effects or reduce the costs of disposal by other means
		5.1.1.3	Through filtration	- Surface water bodies filter air pollution	Mediation through filtration of waste, toxins, and other nuisances by chemical and physical processes of water, ...	... that can protect people
		5.1.1.3	Through sequestration	- Nutrient degradation (phosphorus capture)	Mediation through sequestration of waste, toxins, and other nuisances by chemical and physical water processes, ...	... that can protect people
		5.1.1.3	Through storage or accumulation	- Decommissioning of open-pit mines in order to prevent acid mine drainage (e.g., Udden) - Natural sedimentation of pathogens in a surface water body	Mediation through storage or accumulation of waste, toxins, and other nuisances by chemical and physical water processes, ...	... that can protect people
		2.1.2.3, 5.1.2.1	Through other water-related mediation	- Visually covering the open pit (open-cast) with water and establishing an artificial lake, open pit (open-cast) mining lakes (e.g., Udden)	Other types of water-related mediation of environmental conditions ...	.... that can reduce or mitigate nuisance to people
Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	2.2.1.1	Erosion control	- Stable surface water level to e.g., prevent landslides in Göta Älv river Reed	The regulation in the loss of material, by virtue of the characteristics of aquatic ecosystems or by abiotic water characteristics, ...	... that can protect people from erosion and mitigates or prevents potential erosion damage to human use, health, or safety
		2.2.1.3, 5.2.1.2	Flood protection	- Surface water bodies receive excess water and provide flood protection	The regulation of water flows, by virtue of the characteristics of aquatic ecosystems or by abiotic water characteristics, ...	... that can protect people from flooding and mitigates or prevents potential flooding damage to human use, health, or safety

Table AA2. cont. [6].

Division	Group	Code Used in CICES v 5.1	Class	Examples of Services	Water Clause	Use Clause
		own description based on 5.2.1.2	Prevention of subsidence	- Prevention of subsidence by maintaining a stable groundwater level	The regulation of water flows, by virtue of the characteristics of aquatic ecosystems or by abiotic water characteristics, ...	... that can protect people from subsidence and mitigates or prevents potential subsidence damage to human use, health, or safety
		own description based on 2.2.1.3	Drought attenuation	- A surface water body that retains water and is able to release it slowly - Groundwater leaves the subsurface via springs and wetlands	The regulation of water flows, by virtue of the characteristics of aquatic ecosystems or by abiotic water characteristics, ...	... that can protect people from drought and mitigates or prevents potential drought damage to human use, health, or safety
		2.2.1.5	Fire protection	- Rivers or other surface water bodies as a physical barrier against fires (fire protection belt)	The reduction in the incidence, intensity or speed of fire spread by virtue of the presence of aquatic organisms and the presence of water in the landscape, ...	... that can protect people from fire and mitigates or prevents potential fire damage to human use, health, or safety
	Lifecycle maintenance, habitat and gene pool protection	2.2.2.1, 2.2.2.2	Pollination and spreading of seeds by water	- Seeds of aquatic (macrophytes) and non-aquatic plants that are dispersed by water - Non-aquatic plants: e.g., water mint	The water-related dispersal of seeds and spores, and the fertilization of crops, by aquatic organisms, ...	... that maintains or increases the abundance and/or diversity of organisms that are important to people in use or non-use terms
		2.2.2.3	Maintaining populations and habitats	- The water body provides a natural habitat for species, e.g. (gravel areas for spawning sea trout)	The presence of ecological conditions (usually habitats) and abiotic conditions necessary for sustaining populations of aquatic organisms ...	... that are important to people in use or non-use terms
	Pest and disease control	2.2.3.1, 2.2.3.2	Pest and disease control	- Regulation of pathogens and parasites by (aquatic) organisms, pH, and UV-light	The reduction, carried out by aquatic biological and water interactions or by the presence of water bodies, of the incidence of organisms ...	... that prevent or reduce the output of food, material or energy, or their cultural importance
	Maintaining water conditions	2.2.5.1	Controlling the chemical quality of freshwater	- Managed aquifer recharge - Living processes maintaining the already acceptable water quality	Maintenance of the chemical condition of freshwaters, by aquatic organisms or by abiotic water characteristics, ...	... that enables human use, health, or safety

Table AA2. cont. [6].

Division	Group	Code Used in CICES v 5.1	Class	Examples of Services	Water Clause	Use Clause
	Atmospheric composition and conditions	2.2.6.1, 5.2.1.3	Regulation of global climate	- Lake sediments that accumulate organic matter are effective long-term sinks for carbon (specifically for boreal and northern lakes) - Carbon sequestration in rivers (there is little knowledge about the entire process) - Groundwater as a carbon sink - Methane release from surface water bodies	Regulation of the concentrations of gases in the atmosphere and mediation of gaseous flows by aquatic ecosystems or the water itself, …	… that have an impact on global climate or oceans or offer protection to people
		2.2.6.2, 5.2.2.1	Regulation of local temperature and humidity	- Lake breezes (movement of cool air from across the surface water body toward the land, altering the temperature in regions close to the water body) - Frost occurrences in proximity to big lakes - Springs	Mediation of ambient atmospheric conditions (including micro and mesoscale climates) such as local temperature and humidity, by virtue of the presence of aquatic organisms and abiotic water conditions, …	… that affect people's living conditions, well-being, or comfort
Support to other natural systems					Surface water bodies or aquifers forming input to the functioning of other natural systems …	… that provide regulating services

Table AA3. List of Cultural services from water system service list [6].

Division	Group	Code Used in CICES v 5.1	Class	Examples of Services	Water Clauses	Use Clauses
Direct, in-situ and outdoor interactions that depend on presence in the environmental setting	Physical and experiential interactions with the natural environment	3.1.1.1, 3.1.1.2, 6.1.1.1	Activities promoting health, recuperation, or enjoyment through active, immersive, passive, or observational interactions	- Tourism and recreation through fishing, swimming, nature watching, cave tourism, skating, and skiing - Tourism and recreation through canoeing, sailing, etc.	The abiotic or biophysical characteristics of water or the qualities of aquatic organisms or ecosystems …	… that enable active, or passive, physical and experiential interactions such as use, enjoyment, view, or observation
	Intellectual and representative interactions with natural environment	3.1.2.1, 3.1.2.2, 6.1.2.1	Scientific investigation, creation of traditional knowledge, education, training	- Scientific studies - Outdoor education and excursions - Springs used for environmental monitoring	The abiotic or biophysical characteristics of water or the qualities of aquatic organisms or ecosystems …	… that are the subject matter for in-situ research, teaching, or skill development
		3.1.2.3, 6.1.2.1	Culture or heritage	- Historical understanding through, e.g., agricultural landscapes, historical activities, e.g., log driving and historical artifacts, e.g., water mills	The abiotic or biophysical characteristics of water or the qualities of aquatic organisms or ecosystems …	… that contribute to cultural heritage or historical knowledge
		3.1.2.4, 6.1.2.1	Aesthetic experiences	- Sites of great beauty	The abiotic or biophysical characteristics of water or the qualities of aquatic organisms or ecosystems …	… that are appreciated for their inherent beauty
Indirect, remote, often indoor interactions that do not require presence in the environmental setting	Spiritual, symbolic, and other interactions with the natural environment	3.2.1.1, 3.2.1.2, 6.2.1.1	Religious, sacred, or symbolic meaning	- Sacred springs	The abiotic or biophysical characteristics of water or the qualities of aquatic organisms or ecosystems …	… that have symbolic or spiritual importance such as being recognized by people for their cultural, historical, or iconic character and that are used as emblems or signifiers of some kind, or being deemed to have sacred or religious significance for people
		3.2.1.3, 6.2.1.1	Entertainment or representation	- Possibility for amusement or enjoyment via different media	The abiotic or biophysical characteristics of water or the qualities of aquatic organisms or ecosystems …	… that provide material or subject matter that can be communicated to others via different media for amusement or enjoyment

Table AA3. cont. [6].

Division	Group	Code Used in CICES v 5.1	Class	Examples of Services	Water Clauses	Use Clauses
	Other biotic or abiotic characteristics that have a non-use value	3.2.2.1, 3.2.2.2, 6.2.2.1	Existence, bequest, or option value	- Existence of species, landscape elements, etc.	The abiotic or biophysical characteristics of water or the qualities of aquatic organisms or ecosystems …	… that people seek to preserve because of their non-utilitarian qualities or importance to others and future generations
Support to other natura systems					Surface water bodies or aquifers forming input to the functioning of other natural systems …	… that provide cultural services

Table AA4. Provisioning services list for Bohal Spring source

Sl. no	Division	Group	Class	Important for case study?	Services in the case study	Data source
1	Water	Water for drinking	Municipal and private water supply, for humans	✓	Palampur Municipality Committee depends on the spring to fulfil drinking water need to Palampur. And is also used as source of DW for Bohal village	[40, 24]
2			Drinking water for animals	✓	Dairy and live stocks animals (sheep's and goats)	[40]
3			Reserve water source	✓	Spring water is tapped in spring box	[24]
4		Water for non-drinking purpose	Water used as a material e.g. process water	✓	Used in dairy	[40]

Table AA4. cont. Regulating services list for Bohal Spring source

Sl. no	Division	Group	Class	Important for case study?	Services in the case study	Data source
1	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	Prevention of subsidence	✓	Spring helps in prevention of subsidence by maintaining water table level	[41]
2		Atmospheric composition and conditions	Regulation of local temperature and humidity	✓	Spring regulates the surrounding temperature and humidity	[42]

Table AA4. cont. Cultural services list for Bohal Spring source

Sl. no	Division	Group	Class	Important for case study?	Services in the case study	Data source
1	Direct, In-situ and outdoor interactions that depend on presence in the environmental setting	Intellectual and representative interactions with natural environment	Scientific investigation, creation of traditional ecological knowledge, education, training	✓	Many research for payment of ecosystem services (PES) model which is implemented in Bohal water shed area	[40]
2			Aesthetic experiences	✓	Looking at the scenic beauty around the spring	[40]

Table AA5. Provisioning services list for the Dal Lake

Sl. no	Division	Group	Class	Important for case study?	Services in the case study	Data source
1			Cultivated plants or animals	✓	Vegetables (tomatoes, capsicum, chillies, cabbage, turnips, gaourds, cucumber, lotus stalk, duck potatoes)	[43, 44]

Sl no	Division	Group	Class	Important for case study?	Services in the case study	Data source
		Food			Fruits (watermelon, water chestnuts & lotus fruit) Commercial fishing (common carp, mirror carps, kashir gad, ali gad, chiriv, theta gurun)	
2			Wild plants or animals	✓	Zooplanktons which depends on macrophytes, phytoplankton's & benthos (chironomus, tubifles), algae which can be used for production of food	[28, 44]
3			Fibers and other materials from cultivated plants or animals	✓	The willow and poplar tree plantation used as timber	[44]
4	Biomass (aquatic)	Material	Fibers and other materials from wild plants or animals	✓	Weeds used as compost for the gardens, water lily's petioles and leaves are used as fodder for cattle's	[28, 43]
5			Cultivated plants or animals as an energy source	✓	The willow and poplar tree plantation used as fuel wood	[44]
6		Energy	Wild plants or animals as an energy source	✓	Has the potential of biofuel production (Azolla spp, macrophytes)	[45]
7		Water for drinking	Municipal and private water supply, for humans	✓	Drinking water purposes (on average about 45 million gallons per day (MGD))	[28, 43]
8			Drinking water for animals	✓	Domestic animals which are kept by people in farms on Dal lake	[43]
9	Water	Water for non-drinking pupose	Irrigation	✓	Irrigation for floating gardens and woody vegetation	[46]
10			Water used a material, e.g. process water	✓	Washing clothes	[47]
11		Water for transport	Water as a mean for transportation	✓	Shikara (specialized boat used for local transport within the Dal lake)	[43]
12		Water as foundation	Water used as foundation for floating population	✓	People living on floating house boats which is on the water	[44]

Table AA5. cont. Regulating services list for the Dal Lake

Sl. no	Division	Group	Class	Important for case study?	Services in the case study	Data source
1			Through living processes	✓	Organic elements is dumped into the lake untreated	[36]
2	Transformation of biochemical or physical	Mediation of waste, toxic	Through dilution	✓	Untreated sewage, pesticides and chemicals	[46]
3			Through filtration	✓	Purification of air by floating gardens and forest cover	[43, 44]

Sl. no	Division	Group	Class	Important for case study?	Services in the case study	Data source
4	inputs to ecosystems	substances and nuisances	Through sequestration	✓	Presence of macrophytes, mainly Azolla sp, which helps in CO_2 sequestration	[36]
5			Through storage or accumulation	✓	Plastic and metal waste	[36, 37]
6		Regulation of baseline flows and extreme events	Flood protection	✓	Excess water of Jhelum river flows into Dal lake during flood.	[43]
7			Fire protection	✓	Presence of Wet lands around lake acts as a barrier for the forest fire to reach the houses on the other side and vice versa.	[48]
8	Regulation of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	Pollination and spreading of seeds by water	✓	Some red algae reproduce by spores which are carried by water currents	[49]
9			Maintaining populations and habitats	✓	Potential gene pool conservation for S. niger fishery, home for migratory birds, natural habitat of many species.	[50, 51]
10		Maintaining water conditions	Controlling the chemical quality of freshwater	✓	Presence of Macrophytes	[35]
11		Atmospheric composition and conditions	Regulation of local temperature and humidity	✓	Regulates temperature	[52]

Table AA5. cont. Cultural services list for the Dal Lake.

Sl. no	Division	Group	Class	Important for case study?	Services in the case study	Data source
1	Direct, in-situ and outdoor interactions that depend on presence in the environmental setting	Physical and experiential interactions with natural environment	Activities promoting health, recuperation or enjoyment through active, immersive, passive or observational interactions	✓	Swimming, skiing, bird watching, angling	[43, 51]
2		Intellectual and representative interactions with natural environment	Scientific investigation, creation of traditional ecological knowledge, education, training	✓	Investigations on Macrophytes, wetlands, algae, voluntary conservation activities	[35, 48]
3			Aesthetic experiences	✓	House boat stay to experience natural beauty	[43]
4	Indirect, remote, often indoor interactions that do not require presence in the	Spiritual, symbolic and other interactions with natural environment	Religious, sacred or symbolic meaning	✓	Presence of lotus plants	[44]

	environmental setting					

Table AA6. Added service class, with description of division, group, class, example , water clause and use clause.

Division	Group	Class	Example of services	Water clauses	Use clauses
Water	Water as foundation	Water used as foundation for floating population	-People carrying out their living on floating house boats	Surface water bodies..	…that serves as a foundation for floating population

8.2 Appendix B – Hazard identification

Table BB1. List of identified potential hazard source for Bohal spring according to TECHNEAU hazard database

Hazard	Reference	Hazardous event	Type of hazard	Potential consequences	Present in the study area?	Data source	Hazard source	Specific threat
Contamination of aquifers	2.1.3	Leaching of contaminants by built constructions (e.g. landfills using waste or contaminated ground, dumpsites, traffic facilities, installations for handling, storage and deposition of waste materials or excavation residues, etc.)	Biol., Chemic.	Contaminated water (chemicals)	✓	[40]	Water tank	Potential breakage of water tanks or repair works in future
	2.1.7	Agricultural runoff and leach-out containing fertilizers, sludge, herbicides, etc.	Biol., Chemic.	Contaminated water (pathogens, chemicals)	✓	[40]	Chemical fertilizers and pesticides	
	2.1.8	Manure spread or cattle in the zone	Biol., Chemic.	Contaminated water (pathogens). Nutrient load in water.	✓	[40]	Livestock (sheep, goat and cattle) & organic manure	
	2.1.11	Contamination by forestry activities, wild life activities, natural fowls, dead animals, bird pest (flu)…	Biol., Chemic.	Contaminated water (pathogens, chemicals)	✓	Google maps	Wild life activities (Goral, Barking deer, Sambar, Wild pig), bird pest, natural fowls, Leaf litter	
Shortage of groundwater resources	2.1.13	Groundwater aquifer is not sufficiently fed or water is abstracted by others	Unavailability	Unavailability of raw water	✓	[40]	Not sufficiently fed due to Overgrazing, Leaf fodder extraction	

Table BB2. List of identified potential hazard source for the Dal Lake according to TECHNEAU hazard database

Hazard	Reference	Hazardous event	Type of Hazard	Potential Consequences	Present in the study area?	Data source	Hazard source	Specific threat
Contamination of catchment zone	1.1.2	**Industrial discharge** of biological matter	Biol.	Contaminated water (pathogens)	✓	[28]	Sewage treatment plants (STP's) (Habak STP, Hazratbal STP, Laam STP, Nallah Ameer Khan STP)	Discharge of untreated sewage
	1.1.3	**Emissions during accidents** (fire or explosions) e.g. industrial accidents or forest fire	Chemic.	Contaminated water (chemicals)	✓	[53]	Emissions during accidents	
	1.1.4	**Traffic accidents** with ships, trains, vehicles and planes	Biol., Chemic., Rad/phys., Unavailability, Safety	Contaminated water (chemicals)	✓	[53]	Road accidents of vehicles and houseboat accidents	Accidents
	1.1.5	**Toxic chemicals** from air deposits or air pollution	Chemic., Rad/phys., Unavailability	Contaminated water (chemicals)	✓	Google maps	Air pollution from STP's and exhausts from vehicles	
	1.1.7	**Emissions and leakage**, oil spills (MTBE) by shipping or traffic	Biol., Chemic.	Contaminated water (pathogens, chemicals)	✓	Google maps	Traffic and car cleaning shops along the periphery of the Lake, house boats fuel leakage	Road accidents and overflow by car wash company
	1.1.9	**Latrines** deposits from **boats**, etc.	Biol., Chemic.	Contaminated water (pathogens, chemicals). Nutrient load in water	✓	[44]	Discharge from house boats	
	1.1.10	Intensive **fishery**, fish farming, massive fish death	Biol., Chemic.	Contaminated water (pathogens, chemicals)	✓	[54]	Fish death due to decrease in Oxygen level and introduction of bread variety of fishes like carp and unregular fishing	
	1.1.12	Sewer overflows due to rainfalls or failures	Biol., Chemic.	Contaminated water (pathogens, chemicals). Insufficient raw water	✓	[51]	Sewage overflows due to lack of efficiency	

	1.1.14	Erosion into catchment with release of soil, sand or contaminants	Chemic., Unavailability	Contaminated water (chemicals)	✓	[51]	Silt and sedimentation deposition	
	1.1.19	Disposal of manure	Biol., Chemic.	Contaminated water (pathogens, nutrient load, pharmaceuticals)	✓	[44]	Manure usage in floating farm	
	1.1.20	Runoff from agriculture and urban green areas containing fertilizers, sludge, herbicides, etc	Biol., Chemic.	Contaminated water (pathogens, chemicals, nutrient load)	✓	[51]	Agriculture runoff	
	1.1.22	Discharges of treated wastewater	Biol., Chemic.	Contaminated water (pathogens, chemicals, nutrient load)	✓	[28]	Sewage treatment plants (STP's) discharge (Habak STP, Hazratbal STP, Laam STP, Nallah Ameer Khan STP)	
Contamination of reservoir	1.1.25	**Birds** droppings or animals allowed to cross a protection zone	Biol.	Contaminated water (pathogens)	✓	[44, 51]	Bird droppings and animal waste	
	1.1.26	**Algae blooms** (mostly during summer month's)	Biol., Chemic.	Contaminated water (algae, chemicals, nutrient load)	✓	[44]	Use of fertilizers and pesticides	

8.3   Appendix C – Risk Estimation

The following risk assessment matrix is presented in a rotated (landscape) table. Column groups for the consequence assessment are:

- **Provisional Services:** Municipal Drinking water supply · Drinking water for Animals · Reserve water source · Water used as a material for dairy
- **Regulating Services:** Prevention of subsidence · Springs regulating temperature and humidity
- **Cultural Services:** Scientific investigation, education and training · Looking at springs and surrounding nature
- **Total risk posed by a hazard to all services**

Hazards	Specific threats from hazard		Likelihood	Vulnerability	Municipal Drinking water supply	Drinking water for Animals	Reserve water source	Water used as a material for dairy	Prevention of subsidence	Springs regulating temperature and humidity	Scientific investigation, education and training	Looking at springs and surrounding nature	Total risk
Water tank and Pipe installation for Handling	· Construction or Repair work in future · Damage to Water tank facility	Description	No Protective layer, Spring is directly exposed to irregularities		No Protective layer, contamination, major impact	Short term contamination, major impact	Short term contamination, minor impact	Short term contamination, Insignificant impact	No consequence	No consequence	Small effect if contaminant produces unpleasant odour	Small effect if contaminants doesn't look aesthetic	
		Score	Unlikely 2	5	40	40	20	10	0	0	20	20	130
			Risk = l · v · c										
Agriculture runoff	· Leach-out containing fertilizers	Description	Almost certain	No protective soil layer, slow contaminant degradation	Long-term contamination, major impact	Long-term contamination, major impact	Long-term contamination, major impact	Long-term contamination, moderate impact	No consequence	No consequence	Small effect if contaminant produces unpleasant odour	Small effect if contaminant produces unpleasant colour	
	· Nutrient load (N, P)	Score	5	4	80	80	80	60	0	0	40	40	380
			Risk = l · v · c										
Manure	· Microbial contamination from manure spread	Description	Foreseeable	No protective soil layer, contaminant degradation possible	Short term contamination. Gets decomposed with time, minor impact	Short term contamination. Gets decomposed with time, minor impact	Short term contamination. Gets decomposed with time, minor impact	Short term contamination. Gets decomposed with Insignificant impact	No consequence	No consequence	Small effect if contaminant produces unpleasant odour	Small effect if contaminant produces unpleasant colour	
	· Cattles in the Zone	Score	3	4	36	36	36	24	0	0	24	24	180
			Risk = l · v · c										
Forest activities	· Natural fowls	Description	Foreseeable	No protective soil layer, slow contaminant degradation, good ability to withstand	Short-term contamination, Minor Impact	Short-term contamination, Minor Impact	Short-term contamination, Minor Impact	Short-term contamination, Minor Impact	No consequence	No consequence	Small effect if contaminant produces unpleasant odour	Minor impact on service supply	
	· Spread of plant nutrients · Dead animals and Bird pest	Score	3	3	27	27	27	27	0	0	18	18	144
			Risk = l · v · c										
Less recharge	· Overgrazing and afforestation	Description	Likely	Water source is majorly recharged by precipitation and filtreation through soil; no ability to withstand the event	Major impact on service supply (as community mainly depend on spring)	Major impact on service supply	Moderate impact on service supply (no long-term effect if hazard source is rarely used)	Moderate impact on service supply (as spring water is rarely used)	Major impact	Moderate impact on service supply	Minor impact on service supply	Minor impact on service supply	
	· Shortage of groundwater	Score	4	4	64	64	48	48	64	48	32	32	400
			Risk = l · v · c										
Total risk a WSS is exposed to			Risk = l · v · c		247	247	211	169	64	48	114	134	400

Figure CC1. Risk assessment matrix with detailed list of hazards and specific threats from the hazards for Bohal spring source. The table also presents comprehensive description of consequence (c) scoring.

Figure CC2. Risk assessment matrix with detailed list of hazards and specific threats from the hazards for the Dal lake. The table also presents comprehensive description of consequence (c) scoring.

Figure CC2. cont.

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