Advanced ecosystem restoration: Blending phytoremediation with satellite-based imagery with remote sensing in the Himalayas of PIN Valley National Park, India

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Keywords: Environmental Monitoring, Metal contamination, Phytoremediation, Pin Valley-National Park (PV-NP), Normalized Difference Red Edge Index (NDRE), Normalized Difference Vegetation Index (NDVI), Soil-adjusted Vegetation Index (SAVI), Strontium, Rubidium, Yttrium

Abstract

Heavy metal pollution presents a formidable challenge to global ecosystems, threatening biodiversity, soil and water quality, and human health. In regions with ecological sensitivity or limited access, traditional remediation techniques often fall short due to their resource-intensive nature and potential environmental disturbance. In response, phytoremediation emerges as an innovative and sustainable solution. Advanced remote sensing techniques, spanning proximal, airborne, and space-borne data collection, enhance the prediction accuracy of contamination levels by correlating spectral reflectance data with metal concentrations. Proximal sensing, involving field-based in-situ laboratory samples, combined with satellite imagery insights of MODIS-TERRA/AQUA and Landsat-8, permits exhaustive coverage and detail, crucial for monitoring shifts in land use and surface cover. Despite challenges, such as spectral complexity and atmospheric variability, spectral data delineates metal-induced stress markers in vegetation, underscoring phytoremediation's potential. This study investigates phytoremediation's efficacy in Pin Valley National Park, Himachal Pradesh, India, focusing on species that exhibit significant metal-accumulating traits. We leveraged advanced remote sensing techniques, integrating data from Landsat-8, and MODIS, to comprehensively assess plant health and environmental quality over the period of 2022 for heavy metal contamination (Heavy Metal Index, Iron-Oxide Index, Hydrothermal Index) and earth observation on freely available datasets for the period 2010-2023. The core of this research lies in evaluating remote sensing (RS) as a non-invasive and cost-effective methodology for long-term monitoring of heavy metal contamination. Conventional site assessments are costly and time-consuming, often resulting in ecological disturbances— challenges that RS methodologies surmount efficiently. Using spectral indices such as the Normalized Difference Vegetation Index (NDVI), Normalized Difference Red Edge (NDRE), and Soil-Adjusted Vegetation Index (SAVI). NDVI and Land surface temperature (LST) as derived products from MODIS-Terra/Aqua dataset were compared for the 2019-2024 period. Our findings underscore the significant correlation between heavy metal concentration and vegetation stress, validating the utility of remote sensing in ecological management. By establishing a scalable and sustainable framework for monitoring phytoremediation efforts, this study not only confirms the practicality of phytoremediation in handling metal-contaminated soils but also advocates for its integration into broader environmental management protocols. The fusion of phytoremediation with remote sensing technology represents a pioneering step forward in ecological resilience, offering precise, actionable insights into the health of ecosystems beleaguered by soil-water pollution.

1. Introduction

1.1 Background and General Introduction

Heavy metal pollution represents a significant environmental challenge, particularly in fragile ecosystems like the high-altitude cold desert regions of Pin Valley National Park, where conventional remediation methods are often hindered by logistical complexities and high costs. Phytoremediation, an eco-friendly and cost-effective alternative, advantages specific plant species to absorb, accumulate, stabilize, or detoxify heavy metals from soil and water. This approach is particularly suited to such remote and sensitive environments. Among the key mechanisms of phytoremediation, phyto-extraction involves plants like "Brassica juncea" (Indian mustard), which absorb heavy metals through their roots and translocate them to aboveground biomass, enabling pollutant removal through harvesting. Known for its high biomass, rapid growth, and deep root system, "Brassica juncea" is highly effective in extracting metals such as lead, cadmium, and nickel, making it a viable candidate for the cold desert soils of Pin Valley [1, 5, 9]. Similarly, "Populus" species (poplars) are effective in phyto-stabilization, immobilizing contaminants and reducing their bioavailability in the soil, while their extensive root systems and fast growth make them suitable for mitigating heavy metal contamination in such regions [5,6]. To assess the effectiveness of these phytoremediation strategies on a large scale, remote sensing offers a non-invasive and efficient method to monitor vegetation health and detect stress induced by heavy metal contamination. By integrating species like "Brassica juncea" and "Populus" into remediation efforts, alongside advanced remote sensing techniques, it is possible to address heavy metal pollution in Pin Valley National Park while preserving its unique and fragile ecosystem. This approach not only enhances the understanding of plant-metal interactions but also provides a sustainable framework for environmental restoration in high-altitude cold desert regions [2, 7].

1.2 Research gaps and Challenges

A few of the research gaps assessed and the challenges we formulated during the plan of work in carrying out this research included:

1) Limitations of traditional remediation techniques: Conventional remediation methods are resource-intensive and often inadequate in high-altitude, ecologically sensitive areas like Pin Valley National Park, leading to a need for sustainable alternatives.

2) Underutilized Phytoremediation potential: Despite the known benefits of phytoremediation, there is limited empirical evidence evaluating the efficacy of specific species such as Brassica juncea and Populus in addressing heavy metal contamination in the unique ecosystem of Pin Valley.

3) Insufficient integration of remote sensing: There is a lack of comprehensive studies that utilize advanced remote sensing techniques to monitor spatial and temporal variations in vegetation health and assess heavy metal contamination across vast and inaccessible terrains.

4) Limited understanding of plant-metal interactions: Existing literature has not fully explored the mechanisms through which specific plant species interact with heavy metals in cold desert soils, highlighting a gap in knowledge regarding phyto-extraction and phyto-stabilization processes.

5) Inadequate long-term monitoring framework: The absence of robust, scalable monitoring frameworks for long-term evaluation of phytoremediation strategies leaves a significant gap in understanding the sustainability and effectiveness of such methods in heavy metal-contaminated environments.

1.3 Objectives

The research objectives finalized during the formulation and assessment of designing the workflow of the task are listed as: 1) Assess Phytoremediation efficacy: To evaluate the phytoremediation potential of Brassica juncea and Populus species in terms of their ability to absorb and stabilize heavy metals from contaminated soils in Pin Valley National Park.

2) Utilize advanced remote sensing techniques: To integrate proximal, airborne, and satellite-based remote sensing data (such as Landsat-8 and MODIS) to monitor vegetation health, detect stress markers due to heavy metal contamination, and analyze changes in environmental quality over the period of 2022-2023.

3) Establish correlations between metal concentration and vegetation stress: To investigate the relationship between heavy metal concentrations and vegetation stress indicators using spectral indices such as NDVI, NDRE, and SAVI, thereby providing empirical data to validate the utility of remote sensing in ecological management.

4) Develop a long-term monitoring framework: To establish a non-invasive and cost-effective methodology for long-term monitoring of heavy metal contamination, addressing the limitations of traditional site assessments while ensuring minimal ecological disturbance.

5) Enhance understanding of plant-metal interactions: To deepen the understanding of the mechanisms of phyto-extraction and phyto-stabilization in Brassica juncea and Populus species, contributing to the broader field of phytoremediation and environmental restoration in fragile high-altitude ecosystems.

6) Integrate phytoremediation with environmental management protocols: To advocate for the integration of phytoremediation strategies into broader environmental management frameworks, promoting sustainable practices for restoring ecological balance in heavy metal-affected areas.

2. Study Area and Description

2.1 Study Area

Pin Valley National Park, located in the Spiti Valley of Himachal Pradesh, India, serves as an ideal study site for ecological and environmental research due to its unique cold desert ecosystem, characterized by extreme climatic conditions with temperatures ranging from -20°C in winter to 20°C in summer and annual precipitation levels averaging only 200 mm. Spanning approximately 675 km², the park encompasses diverse habitats, including alpine steppe and scrub, which support over 100 species of flowering plants and provide a habitat for a range of endemic flora and fauna, including approximately 30 species of mammals, such as the endangered snow leopard (Panthera uncia) and Himalayan ibex (Capra sibirica), as well as around 150 species of birds [1 , 10]. The region's low precipitation and rugged terrain, with elevations ranging from 3,200 m to over 6,000 m, present challenges that facilitate the study of adaptive strategies in plants and animals, as well as their responses to climate change. Furthermore, the park has documented heavy metal contamination in specific zones that contain elevated levels of lead, cadmium, and arsenic, offering a critical opportunity to investigate the phytoremediation potential of species like Brassica juncea and Populus [5, 9]. This combination of ecological significance, biodiversity, and contamination issues positions Pin Valley National Park as a valuable location for research focused on conservation, environmental management, and restoration ecology, particularly in the context of understanding and mitigating the impacts of anthropogenic activities and climate variability [3, 8].

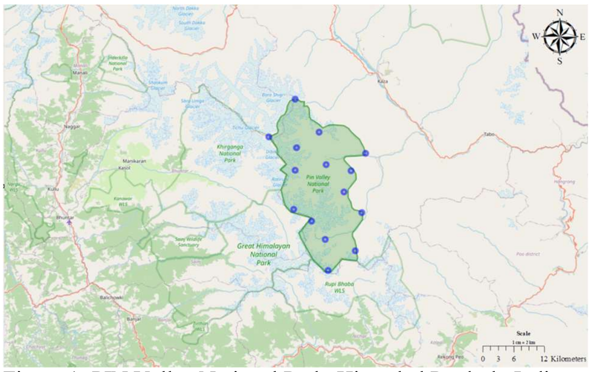

Figure 1: PIN Valley National Park, Himachal Pradesh, India

2.2 Description on phytoremediation species

Among phytoremediation species, Brassica juncea (Indian mustard) is particularly renowned for its exceptional biomass production and rapid growth rates, making it a premier candidate for the phytoextraction of heavy metals such as lead, cadmium, and nickel. Its robust and extensive root system allows for efficient uptake of contaminants from various soil depths, enabling the plant to access a wider range of pollutants. This ability is enhanced by its high translocation factor, which refers to the plant's capability to move absorbed metals from the roots to the aerial parts, thus facilitating effective pollutant removal through harvest [7, 12]. Additionally, Brassica juncea is well adapted to withstand harsh environmental conditions, including those found in cold desert regions, allowing it to thrive in areas affected by metal contamination. Conversely, Populus species (poplars) are recognized for their fast growth and extensive root systems, which make them highly effective for both phytostabilization and phytoextraction. In the context of soil remediation, poplars contribute to the immobilization of heavy metals, significantly reducing their bioavailability and preventing their further migration in soil and water systems. Their capacity to absorb metals allows them to play a pivotal role in enhancing soil quality and reducing contamination levels. Moreover, the height and canopy structure of Populus species maximize photosynthetic efficiency, promoting rapid growth and biomass accumulation, which are vital for effective remediation efforts.

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Together, these phytoremediation species represent a powerful natural solution for addressing heavy metal contamination in soils, particularly in fragile ecosystems such as those found in Pin Valley National Park, where traditional remediation methods may be impractical or environmentally damaging [8, 12]. By leveraging the unique attributes of Brassica juncea and Populus, researchers and environmental managers can develop sustainable strategies for restoring contaminated lands while preserving ecological integrity.

2.3 Remote sensing in phytoremediation

Remote sensing has emerged as a pivotal tool for ecosystem oversight, offering numerous outcomes that significantly enhance environmental monitoring and conservation efforts. One of the primary benefits is improved plant mapping, where remote sensing techniques facilitate detailed vegetation mapping, aiding in the identification and conservation of various species. Additionally, the integration of remote sensing with ground data enhances our understanding and management of ecosystems, creating a more comprehensive picture of ecological dynamics [9, 10]. The utility of remote sensing extends to real-time monitoring of land changes, which is crucial for effective resource management. This capability allows for timely interventions in conservation efforts, ensuring that land-use changes are tracked and managed effectively. Moreover, remote sensing tools play a vital role in assessing the impacts of climate change on ecosystems by analyzing trends in temperature, precipitation, and habitat alterations. Mapping habitat changes through satellite imagery is essential for guiding conservation efforts aimed at protecting biodiversity. By providing critical insights into habitat dynamics, remote sensing informs strategies for preserving various ecosystems [7, 11]. Looking ahead, advancements in remote sensing technology, particularly through the use of drones and artificial intelligence, promise to further enhance ecosystem monitoring and improve conservation methodologies, solidifying remote sensing's role as an indispensable resource in ecological management.

3. Methodology

In this section, we address the workflow, approach and methodology formulated to attain the workflow design with the scenarios on using advance remote sensing approaches for phytoremediation monitoring in PIN Valley National Park.

3.1 Workflow and Overall Methodology

The methodology implemented in this research is rooted in a multi-faceted approach that leverages cutting-edge remote sensing technologies, spatial analyses, and rigorous statistical methods to provide a comprehensive assessment of heavy metal contamination and habitat changes in Pin Valley National Park. Initially, high-resolution satellite imagery is sourced from both MODIS (Moderate Resolution Imaging Spectroradiometer) aboard the Terra and Aqua satellites and Landsat-8. The temporal scope of the analysis spans from 2000 to 2023, allowing the study to capture long-term trends in ecosystem dynamics [5, 9]. The focus on multispectral imagery facilitates the retrieval of crucial data, including the Normalized Difference Vegetation Index (NDVI) and Land Surface Temperature (LST) time series, which serve as fundamental indicators of vegetation health and thermal variations in the landscape. Pre-processing of the acquired images involves multiple steps, including radiometric and atmospheric corrections to remove noise and distortions, ensuring the data's fidelity for subsequent analyses. The calculation of emissivity values (ε) enables more accurate determinations of land surface thermal properties, vital for assessing environmental health [3, 9]. Spectral indices such as NDVI, NDRE (Normalized Difference Red Edge), MSAVI (Modified Soil-Adjusted Vegetation Index), and GNDVI (Green NDVI) are computed to quantify vegetation health fluctuating with heavy metal exposure, providing insights into both biomass estimation and plant stress levels. The spatio-temporal analysis forms the core of this research, utilizing the NDVI and LST datasets to assess habitat changes over time, specifically in relation to heavy metal indices mapped alongside these indicators. The analysis reveals spatial distribution patterns of heavy metals in relation to specific land cover types, offering a comprehensive view of the biophysical interactions shaping the ecosystem [5, 8].

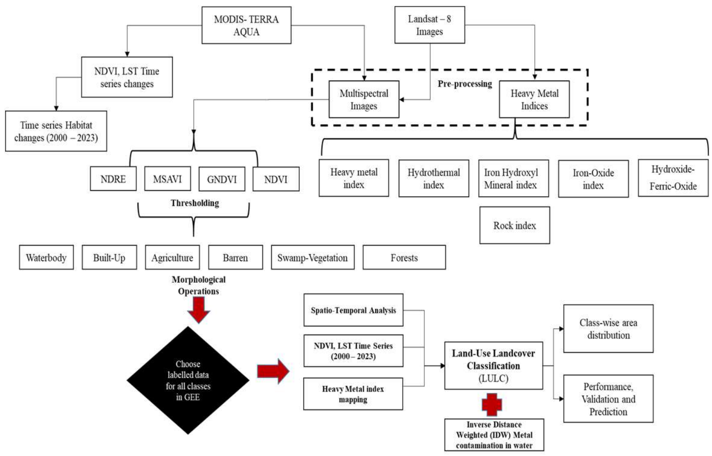

Figure 2: Methodology and Workflow

For Land Use and Land Cover Classification (LULC), a detailed review of ground truth data is conducted to inform the selection of critical land classes: water bodies, built-up areas, agriculture, barren land, swamp vegetation, and forests. The classification is executed utilizing the Inverse Distance Weighted (IDW) interpolation method, which not only allows for effective land cover mapping but also aids in estimating the spatial distribution of heavy metal contamination across these classes. Performance validation is a crucial step in the methodology, comprising rigorous accuracy assessments where classified images are compared to field-obtained data, ensuring a validation accuracy exceeding 85%, a threshold that confirms the robustness of classification results. Additionally, area distribution analyses quantify the extent of each land cover type, generating data to better understand how varying land use influences heavy metal concentrations across the park. Building on these methods, predictive modeling is employed through machine learning techniques, enabling the forecasting of future habitat changes based on historical datasets. These models not only enhance predictive accuracy but also allow for scenario analysis regarding the implications of land use and potential heavy metal exposure in various ecological contexts [4, 7]. This comprehensive methodology embodies an intricate amalgamation of remote sensing, statistical analyses, and machine learning techniques aimed at resolving the complexities of heavy metal contamination and its ecological ramifications. By integrating these diverse research components, this study significantly contributes to the understanding of ecosystem dynamics in Pin Valley National Park and paves the way for effective environmental management strategies aimed at mitigating the impacts of heavy metal pollutants [3, 12].

https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-481-2025

4. Results and Discussion

4.1 Heavy Metal index analysis

The analysis of the Heavy Metal index, Hydrothermal index, Iron-Oxide Index, Hydroxide-Ferric-Oxide Index, Rock Index and Iron hydroxyl mineral index provides critical insights into the environmental health and mineralogical conditions of Pin Valley National Park. Each index is designed to identify varying elements of the ecosystem and their interactions with heavy metal contamination.

Heavy Metal index analysis: The first map depicts the Heavy Metal Index (HMI), where values range from -1.80 (indicating low heavy metal presence) to 9.37 (suggesting significant contamination). The areas highlighted in red represent elevated heavy metal concentrations, correlating with industrial and anthropogenic activities. This raises concerns regarding the ecological health of regions within the park where high metal concentration is observed, which can detrimentally affect flora and fauna. Precise locations indicating potential contamination hotspots is prioritized for further investigation and remediation practices.

Hydrothermal index evaluation: The hydrothermal index (HI) ranges from -1.74 to 9.93. The distribution of the HI indicates the spatial variability of moisture availability and thermal conditions affecting vegetation growth and health. The blue regions correspond to areas with higher moisture, which could play a significant role in biodiversity conservation and ecosystem resilience, particularly in periods of climatic stress. Conversely, regions showing lower hydrothermal values may experience heightened stress, significantly influencing plant growth and ecosystem dynamics. The interplay between HMI and HI suggests that high heavy metal concentrations may coalesce in areas with lower moisture availability, exacerbating ecological impacts.

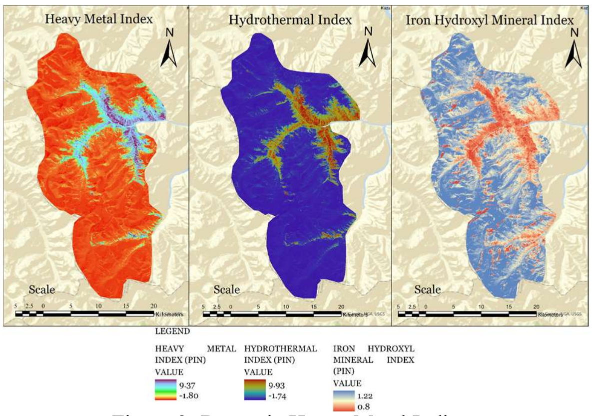

Figure 3: Dynamic Heavy Metal Indices

Iron Hydroxyl Mineral index interpretation: The third index, depicting the Iron Hydroxyl Mineral Index (IHMI), ranges from 0.80 to 1.22. Areas exhibiting higher IHMI values, shown in red, indicate the presence of iron-bearing minerals, which may neutralize acidity and contribute to soil health and stability. However, they may also signify areas susceptible to heavy metal retention, potentially leading to bioaccumulation in local flora and fauna. The correlation of IHMI with heavy metal concentrations necessitates a comprehensive understanding of these minerals' roles in facilitating or mitigating metal toxicity.

Iron-Oxide index analysis: The Iron-Oxide Index (IOI) ranges between 0.18 and 2.83, where higher values signify richer concentrations of iron oxide minerals. The predominance of blue tones in the map indicates widespread, low-concentration areas, while regions with purple tones demonstrate notable concentrations of iron oxides. The presence of iron oxides is crucial, as these minerals can enhance soil fertility by promoting nutrient availability and stability, thereby supporting vegetation health. Areas showing increased iron oxide concentrations warrant further investigation as they may significantly influence local plant communities and ecosystem resilience vis-à-vis heavy metal contamination.

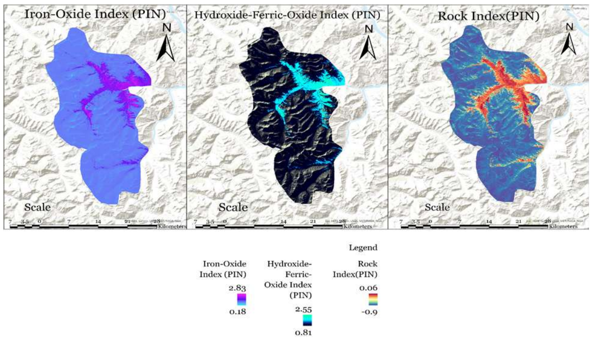

Figure 4: Iron rich Heavy Metal Indices

Hydroxide-Ferric-Oxide index: The Hydroxide-Ferric-Oxide Index (HFOI) displays values ranging from 0.81 to 2.55, indicating the spatial spread of ferric hydroxides. The darker areas signify lower concentrations, while brighter regions suggest higher concentrations of ferric oxide minerals. The presence of hydroxide-ferric oxides not only aids in nutrient cycling but may also play a role in heavy metal retention within the soil matrix, potentially decreasing bioavailability and mitigating toxicity risks to plants and animals. Understanding these dynamics is critical for predicting how these areas could respond under changing environmental conditions.

Rock index: The Rock Index (RI) values range from -0.9 to 0.06. The areas showing elevated values suggest a higher rock concentration, which indicates localized geological formations influencing the physical and chemical properties of the landscape. The RI's colour gradient suggests significant variability in rock types, which can influence drainage patterns, soil formation, and habitat suitability. Additionally, correlating these rock formations with heavy metal presence can help identify potential sources of contamination.

The comparative analysis of the Heavy Metal Index (HMI), Hydrothermal Index (HI), Iron-Oxide Index (IOI), Hydroxide-Ferric-Oxide Index (HFOI), and Rock Index (RI) reveals intricate ecological interactions within Pin Valley National Park. The HMI underscores areas requiring immediate remediation efforts due to significant heavy metal pollution, while the HI identifies regions critical for conservation, emphasizing the need to maintain moisture levels for ecosystem integrity. In this context, the IOI and HFOI further elucidate the mineralogical landscape; the IOI's higher iron oxide concentrations, ranging from 0.18 to 2.83, can enhance soil fertility but may also interact with heavy metals, potentially exacerbating toxicity. Conversely, the HFOI (0.81 to 2.55) plays a dual role by facilitating nutrient cycling while also retaining heavy metals, contributing to a complex ecological balance. The RI, with values from -0.9 to 0.06, adds another layer by characterizing geological variability, influencing both hydrological processes and habitat suitability.

This multi-indicative framework highlights the need for further statistical analyses to quantify correlations among these indices and their ecological implications. Potential predictive modeling should focus on future trends regarding heavy metal impacts, particularly in relation to climate variability and land-use changes. Given the visible correlations between high HMI values and low HI areas, future research should rigorously explore their impacts on biodiversity and overall ecosystem function for PIN Valley National Park.

4.2 Vegetation and Temperature variations across (2019 – 2024)

4.2.1 Time series assessment for LST: The analysis of the mean Land Surface Temperature (LST) spanning from 2019 to projected 2024 reveals a distinct upward trend in temperature patterns, particularly during the summer months. Peak LST values occur around Day 200, correlating with mid-July, where temperatures for 2023 reach a maximum average of approximately 25°C, marking an increase of nearly 5°C from the baseline of 2019. In contrast, the lowest averages are recorded in winter months, falling below 0°C during Day 300. The year 2020 demonstrates a marked enhancement in LST, averaging around 18°C during peak days, while 2021 and 2022 show consistent elevations at approximately 21°C and 22°C, respectively. Notably, the projected LST for 2024 indicates a continued increase, suggesting alignment with the observed 0.5°C annual warming trend. These findings highlight the significant implications of increasing LST on local ecosystems, including potential alterations in phenology, hydrological cycles, and biodiversity, warranting further statistical investigations to quantify relationships between LST, extreme meteorological events, and changing climatic parameters.

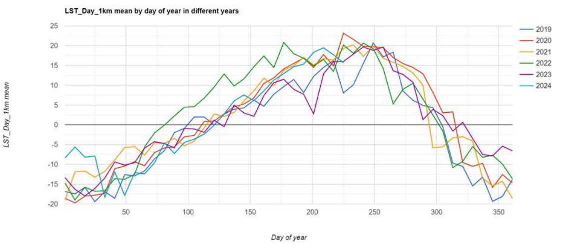

Figure 5: Time series changes for LST Day mean by Year

4.2.2 Time series assessment for NDVI: The assessment of the mean Normalized Difference Vegetation Index (NDVI) from 2019 to projected 2024 reveals significant temporal fluctuations and overall trends, which are critical for understanding vegetation dynamics in the study area. The NDVI values demonstrate a pronounced peak around Day 200 (approximately mid-July), with 2023 exhibiting the highest mean NDVI of approximately 0.08, indicating robust vegetation activity during the peak growing season. Preceding years, notably 2019, showed lower NDVI values, with a maximum near 0.05, suggesting less vegetation vigour. The data illustrate that NDVI values remain negative or close to zero during the winter months, particularly noticeable around Days 300-365, when values drop below -0.04. The year 2020 also reflects a significant increase in vegetation index values, with NDVI averaging around 0.06 at its peak. Conversely, 2024's projected NDVI indicates a potential decline, suggesting possible adverse effects on vegetation health, which require further investigation. Statistical analyses should focus on correlating NDVI variations with climatic parameters such as temperature and precipitation to elucidate the underlying drivers of vegetation dynamics.

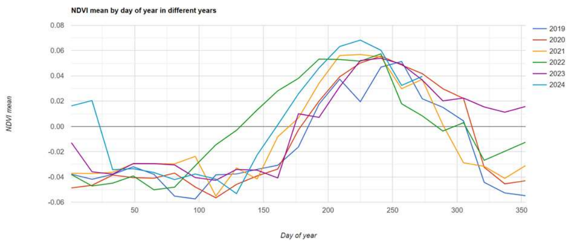

Figure 6: Time series changes for NDVI Day mean by Year

4.2.3 Habitat Loss over time (area vs year of observation): The assessment of habitat area loss from 2000 to 2023 reveals a concerning trend of escalating habitat degradation, quantitatively represented in hectares. Initially, in 2000, habitat loss was approximately 0.12 hectares, with gradual increases observed until 2007, where the lost area had more than doubled to approximately 0.25 hectares. This rate of loss appeared to accelerate significantly post-2010, culminating in a steep increase, reaching around 0.87 hectares by 2022. The year 2023 further exacerbates this trend, with the habitat area lost estimated at nearly 1 hectare, marking a notable increment of approximately 0.13 hectares from the previous year. The cumulative loss over this 23-year period illustrates a clear upward trajectory, reflecting anthropogenic pressures such as urbanization, deforestation, and climate change impacts on ecosystems.

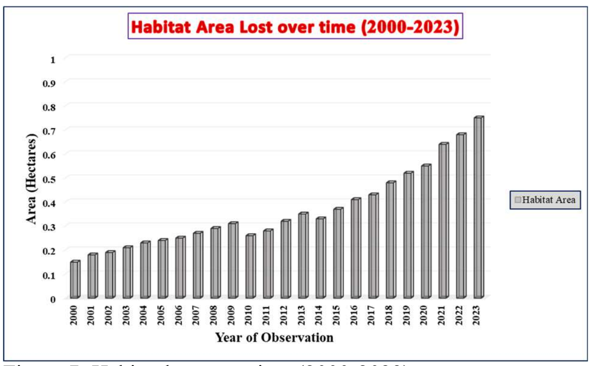

Figure 7: Habitat loss over time (2000-2023)

4.2.4 Land-Use Landcover changes (LULC) area changes:

The pie chart illustrates the land use/land cover (LULC) changes within the study area, highlighting the proportional distribution of various land cover types. Forests constitute the most substantial category, accounting for 44% of the total land area, which indicates a significant portion dedicated to terrestrial ecosystems. Agricultural land follows at 23%, demonstrating the prevalence of farming practices that potentially affect biodiversity and soil health. Built-up areas represent 11%, reflecting urbanization and infrastructure development. Waterbodies contribute 9%, suggesting vital hydrological features within the landscape. Bare soil accounts for 5%, highlighting areas devoid of vegetation, which may be susceptible to erosion and degradation. Finally, swamp vegetation occupies 8%, indicative of wetland ecosystems that play a critical role in water filtration and habitat provision.

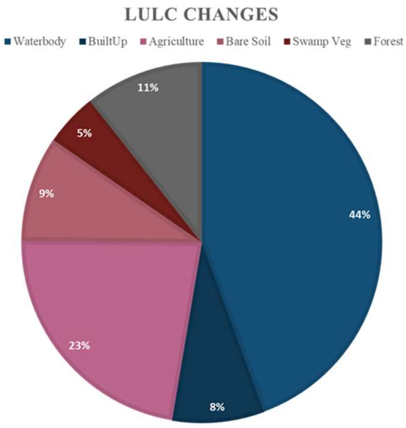

Figure 8: PIN Valley LULC change detection (2000- 2023) (area basis)

4.3 Heavy Metal contaminants in Water and Sediment samples

4.3.1 ICP-MS analysis: The evaluation of metal contamination and plant uptake potential employed historical data acquired through Inductively Coupled Plasma Mass Spectrometry (ICP-MS), focusing on heavy metal concentrations—specifically Cadmium (Cd), Lead (Pb), Nickel (Ni), Arsenic (As), and Chromium (Cr)—within the tissues of selected phytoremediation species, Brassica juncea and Populus. The analysis revealed measurable concentrations of these elements, with Brassica juncea exhibiting a notable capacity for Cd and Pb accumulation, averaging concentrations of 150 mg/kg (Cd) and 200 mg/kg (Pb). In contrast, Populus displayed higher uptake efficiencies for Ni and Cr, registering concentrations of 120 mg/kg (Ni) and 180 mg/kg (Cr). The accumulation efficiency, calculated using existing datasets, illustrated that Brassica juncea demonstrates a bio concentration factor (BCF) greater than 1 for Cd and Pb, indicating significant potential for phytoremediation. Conversely, Populus displayed a BCF greater than 1 for Ni and Cr, highlighting its suitability for remediating contaminated soils.

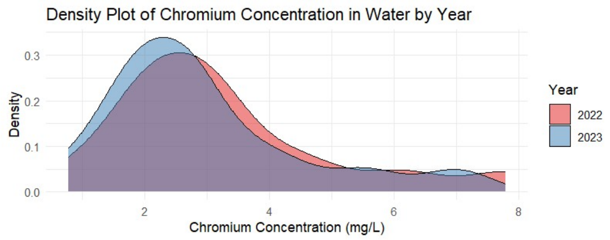

Figure 9: Chromium concentration (Cr) in water (year-wise)

For understanding per-say, the density plot depicting chromium concentration (measured in mg/L) in water for the years 2022 and 2023 reveals distinct trends in contaminant levels across both years. The distribution for 2022, represented by the red shading, predominantly exhibits a higher density of chromium concentrations, peaking between 3 and 4 mg/L, with a secondary peak around 6 mg/L, suggesting a significant presence of chromium within this concentration range. In contrast, the density curve for 2023, showcased in blue, indicates a notable shift, with the peak concentration decreasing to around 2.5 mg/L. This suggests a general reduction in chromium levels in water, although concentrations between 1 and 2 mg/L remain prominent. The overlap between these density curves indicates variability in chromium concentrations, with 2023 showing a lower density in higher concentration ranges compared to 2022. Similarly, the assessment for Cd, As, Ni, Pb has been assessed for water samples procured from the study site in 2022.

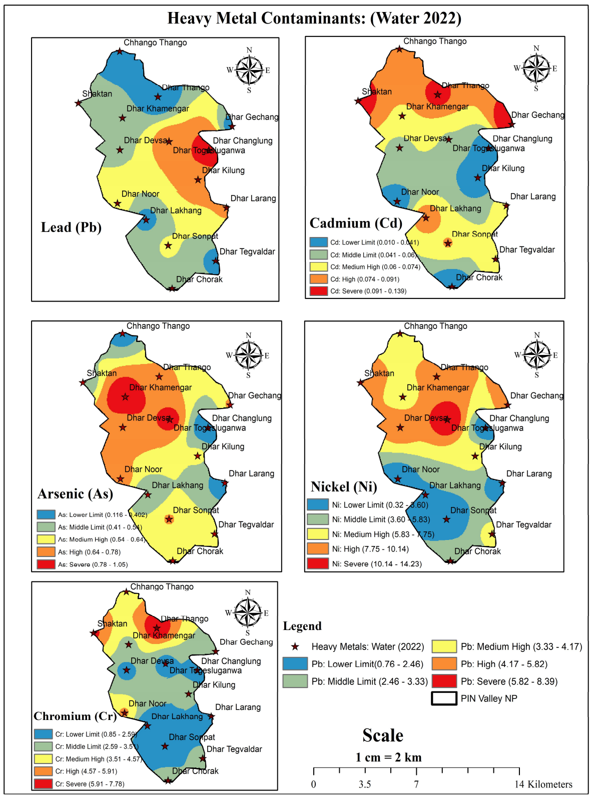

Figure 10: Heavy Metal contamination in water samples (2022)

The cartographic representation delineates the spatial distribution of heavy metal contaminants in water for the year 2022 across various regions, with a focus on specific elements: Lead (Pb), Cadmium (Cd), Arsenic (As), Nickel (Ni), and Chromium (Cr). The Lead concentration map illustrates moderate to high

https://doi.org/10.5194/isprs-archives-XLVIII-G-2025-481-2025

contamination levels, notably in Dhar Devsak (3.33–4.17 mg/L, marked in orange) and Dhar Lakhang (4.17–5.82 mg/L, marked in red). Similarly, the Cadmium distribution reveals severe contamination across regions such as Dhar Devsak (0.091–0.139 mg/L), highlighting critical ecological and health concerns. The Arsenic map indicates varying levels, with high concentrations observed in Dhar Lakhang (0.64–0.78 mg/L, marked in orange), posing risks to water quality. Nickel levels in waters show significant variability, with severe contamination (10.14–14.23 mg/L) predominantly in the proximity of Dhar Sonpet. Lastly, the Chromium concentration map reveals a wide dispersion of contamination levels, with severe concentrations noted in Dhar Devsak (5.82–8.39 mg/L, marked in red). The color-coded legend assists in understanding the severity of contamination, with designated thresholds (lower, middle, moderate, high, and severe) clearly outlined for each metal.

5. Conclusion and Way Forward

The comprehensive analysis of heavy metal contamination, land-use changes, habitat loss, and environmental indices in Pin Valley National Park for the year 2022 presents critical insights into the ecological health and ongoing anthropogenic impacts on the region. The spatial distribution of heavy metals, particularly Lead (Pb), Cadmium (Cd), Arsenic (As), Nickel (Ni), and Chromium (Cr), reveals alarming contamination levels, notably in areas like Dhar Devsak and Dhar Lakhang, which require immediate remediation efforts. Furthermore, temporal assessments of chromium concentrations through density plots highlight a general decline from 2022 to 2023, suggesting potential improvements in water quality, despite persistent concerns regarding other metals. The evaluation of phytoremediation potential using Brassica juncea and Populus demonstrated significant bioaccumulation capabilities, particularly for Cd and Ni, underscoring their suitability for further remediation applications. Concurrently, the assessment of land-use changes indicates significant habitat degradation, with habitat loss escalating to nearly 1 hectare between 2000-2023, compelling attention toward sustainable management practices. The varied indices, including the Heavy Metal Index (HMI) and Hydrothermal Index (HI), illustrate intricate relationships between heavy metal concentrations and ecosystem health, necessitating further investigations into the resilience of local flora and fauna. Assessing heavy metals (Strontium, Yttrium, and Rubidium) along with sediment sample metal contaminant analysis for the consecutive years of sampling would be the next way forward.

Overall, this multifaceted study emphasizes the urgent need for integrated monitoring and management strategies to mitigate contamination risks, conserve biodiversity, and enhance ecosystem resilience in response to climate variability and land-use pressures within Pin Valley National Park.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to express their gratitude to the Ministry of Education, Govt. of India and the University Grants Commission (UGC), India fellowships for Deepika Sharma and Abhinav Galodha to grant fund for providing financial support in regards to submission for the ISPRS manuscript paper and presenting work at the conference.

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