



British Geological Survey



Assessing the hydrological mechanisms and impacts on groundwater of the 2023 flooding in Himachal Pradesh and Punjab

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ENVIRONMENTAL CHANGE, ADAPTATION AND RESILIENCE
PROGRAMME

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Aftermath of floods in
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Credit: Dr Vivek Gupta, IIT
Mandi

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Assessing the hydrological mechanisms and impacts on groundwater of the 2023 flooding in Himachal Pradesh and Punjab

British Geological Survey, National Institute of Hydrology, and
Indian Institute of Technology Mandi

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Foreword

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Executive summary

Following severe and successive flooding in Himachal Pradesh (HP) and Punjab in July and August 2023, the British Geological Survey (BGS), in partnership with the National Institute of Hydrology (NIH) Roorkee and the Indian Institute of Technology (IIT) Mandi, undertook a study to investigate flood mechanisms in the upland areas of HP and the impacts on downstream groundwater in Punjab. The aim of this project was to constrain the scale of the extreme events that occurred in HP and Punjab during the 2023 monsoon and to assess their cumulative impact on groundwater recharge and contamination. The objectives were:

- characterise flood dynamics, cumulative impacts of persistent rain and the role of dams during flooding in the mountains (HP) and plains (Punjab)
- quantify the impacts of floods on groundwater levels and recharge in Punjab, and relate this to upstream and downstream flood characteristics
- quantify flood impacts on groundwater quality in Punjab

FLOOD CHARACTERISTICS, CUMULATIVE IMPACTS AND ROLE OF DAMS

A detailed spatial analysis of observed precipitation revealed that, between 9 and 11 July 2023, intense rainfall occurred across both HP and Punjab. The Beas Basin in Punjab recorded peak rainfall of 126.4 mm on July 9, while the Beas Basin in HP received 106.4 mm. These heavy precipitation events led to widespread river flooding in HP and pluvial flooding in Punjab. Severe river flooding in Punjab was avoided because increased inflows were absorbed by the Pong Dam reservoir during the flooding in July.

The heavy rainfall contributed to sustained elevated soil moisture levels across both states. These conditions influenced the hydrological response of the region, creating a scenario where subsequent rainfall in August was more readily converted into runoff, thereby amplifying the severity of the August flooding. Thus, the hydrometeorological conditions (particularly elevated soil moisture) prior to flooding in Punjab in August 2023 were significantly influenced by the prior rainfall events in July.

Punjab experienced severe flooding from 15 to 17 August and 23 to 25 August 2023. Flooding from 15 to 17 August was primarily triggered by intense rainfall (102.5mm) over the Beas River Basin in HP on 14 August. This excess rainfall over the upstream region resulted in significant runoff that travelled downstream to Punjab through the Pong Dam, which was close to capacity following the July flooding. Subsequent flooding from 23 to 25 August was primarily associated with localised heavy rainfall in regions bordering HP and Punjab, and the continued release of excess runoff from the upstream dams such as the Pong Dam.

The recurring flood events in the region were primarily triggered by episodes of extreme precipitation, underscoring the need for a detailed analysis of rainfall extremes to better understand their evolving characteristics and associated flood risks. Rainfall during the July and August events exceeded average daily monsoon precipitation by around 400%, but overall monsoon precipitation totals in 2023 did not deviate significantly from the long-term mean. Analysis of rainfall data from 1980 to August 2023 highlights a resurgence of prolonged heavy rainfall events in the Beas Basin in Punjab and a partial resurgence in HP and reveals increasing intensity of single-day rainfall events that will increase flood risk in future. At the same time, a significant reduction in total annual precipitation has occurred since the 1990s across both states, with a modest recovery in recent years. Across the rest of Punjab (that is, outside the Beas Basin) there is little evidence of a resurgence of prolonged heavy rainfall events, but this may be affected by the density of rainfall monitoring stations.

The Pong Dam was crucial in regulating the flow of water during the flooding in July and August, limiting the flow into Punjab and helping avoid significant flooding in the downstream areas. Dam operation during the flooding effectively reduced the population exposed to flood impacts in Punjab by 78.7% compared to a modelled, undammed scenario. However, this also limited the potential for groundwater recharge downstream from river flood waters. In addition, our hydrometric and modelling analyses clearly demonstrate the effect of the preceding conditions (increased soil moisture) on surface runoff and consequential flow into the Pong Dam. While the

2023 events are a demonstration of a well-managed event, they highlight the need for dam managers to receive early warnings on soil moisture and meteorological conditions.

Policy implications

RELEVANCE OF ANTECEDENT CONDITIONS FOR DAM MANAGEMENT AND EARLY WARNING SYSTEMS

Hydrometric and modelling analysis clearly demonstrate the importance of preceding conditions (increased soil moisture) for surface runoff and flow into dams, which impact dam releases. Such data should be provided in a form that allows rapid, active and actionable decisions to be made.

USE OF SATELLITE AND MODEL-BASED FLOOD RECONSTRUCTIONS

The successful use of Sentinel and Landsat imagery combined with comparative model scenarios (for example, with and without dam influence) suggests these tools could be integrated into a standard framework for flood mapping and impact assessment. This is particularly valuable in areas where field access is constrained, or post-event surveys are delayed. Expansion of this approach into near-real-time analysis would also support disaster response efforts, early warning systems and dam management.

INCREASED RAINFALL MONITORING DENSITY

For real-time analysis and early warning, increased density of rainfall monitoring is needed, particularly in upstream regions, because re-analysis products smooth out rainfall patterns and do not have sufficient spatial or temporal resolution.

IMPACTS OF FLOODING ON GROUNDWATER LEVELS

Groundwater level data was collected from the Punjab Water Resources Department (WRD) and the Central Groundwater Board (CGWB). Of groundwater sites investigated in Punjab, 69% showed a small but clear response to the floods in July and August. Three distinct patterns of response were identified. The first of these, which represented approximately 36% of sites, displayed a higher peak groundwater level in response to the first flood event in July, which was mainly driven by high rainfall that occurred in Punjab. These sites tended to be clustered in northern and eastern areas of Punjab and appear to correlate with local rainfall anomalies. Another group (21% of sites) saw similar responses to the July and August flood events with no distinct spatial distribution. The third category, representing approximately 18% of sites, displayed a higher peak groundwater level in response to the flood events in August, with these sites tending to cluster in the south and west of the study area, and appearing to correlate with river flooding.

The higher river stages in August were primarily associated with localised heavy rainfall in regions bordering HP and Punjab, which increased flows and necessitated the release of excess runoff from the upstream dams. Therefore, initial analysis suggests distinct groundwater responses to pluvial and river flooding. Isotope analysis, which allows the source of recharge to be fingerprinted, and environmental tracer data (particularly sulphur hexafluoride, SF₆), which indicates the proportion of modern recharge, support the findings of the groundwater level data analysis and provide evidence for recent ingress of water relative to baseline monsoon conditions, most likely because of flooding in July and August 2023.

CFC-12 results from a subset of the sites did not show younger mean recharge ages; however, tritium (³H) analysis for a large sample set showed evidence for recent recharge, corroborating the isotope results. While clear, short-term impacts on groundwater levels were identified, analysis of longer-term data indicate that the floods did not alter long-term trends in Punjab. In Malwa region, 45% of wells with sufficient long-term data had stable groundwater level behaviour, 28% showed a declining trend, and 8% a rising trend.

Policy implications

INVESTIGATING THE USE OF FLOOD WATER AND OPTIMISED DAM MANAGEMENT TO ENHANCE GROUNDWATER RECHARGE

Our results highlight the important role of the dams in mitigating downstream flooding. It is possible that dams could be managed more effectively throughout the year to optimise different needs (for example, electricity generation vs. flood alleviation), including enhancing surface water distribution for agricultural needs and even groundwater recharge.

ENHANCED GROUNDWATER MONITORING NETWORKS

High-resolution groundwater level data improves understanding recharge processes and enables better analysis of extreme events. Extension of high-resolution groundwater level monitoring across Punjab is recommended. High-resolution monitoring should be prioritised where there is significant groundwater extraction for irrigation, water supply or where managed aquifer recharge is taking place.

IMPACT OF FLOODING ON GROUNDWATER QUALITY

In situ specific electrical conductivity (SEC) measurements (a proxy for groundwater salinity) showed an increasing trend, independent of the flooding event, over time at sites with historic data from 2021 and 2022 that were re-measured in 2024. Thus, floods such as those that occurred in 2023 do not appear to attenuate increasing groundwater salinity in the region. There were strong regional differences, with SEC values in the Bist-Doab region averaging 887 $\mu\text{S}/\text{cm}$ and samples from the Malwa region averaging 2415 $\mu\text{S}/\text{cm}$. Major and trace elements highlight poor water quality, especially in the Malwa region, but with limited difference between a small subset of historical data from pre- and post-flood data in 2022 and 2024. It is possible that some of these contaminants, particularly nitrate, may have been mobilised during flooding. However, a better baseline with several years of seasonal data would be required to confirm flood-induced changes in groundwater quality.

Policy implications

DEVELOPING BASELINE WATER QUALITY DATA

A long-term, seasonal water-quality monitoring programme should be established in Punjab. This would allow for improved interpretation of future flood impacts on groundwater chemistry and provide a stronger baseline against which to assess change. Monitoring should include both major ions and trace contaminants, with a particular focus on nitrate, fluoride and heavy metals, including arsenic, uranium and manganese.

STAKEHOLDER ENGAGEMENT

Stakeholders in HP and Punjab have been engaged throughout the project. Project team members presented and discussed the plans for the project with stakeholders at FCDO workshops in Shimla in March 2024 and in Chandigarh in April 2024. The project team organised a stakeholder workshop in July 2024 to present emerging findings and further stakeholder input. A final dissemination workshop took place in Chandigarh in March 2025. The project supported two training courses on the use of environmental tracers in water resource management for a group of 60 students, research scholars and academic laboratory staff from across India.

CONCLUSIONS

This project has allowed us to:

- constrain the extent of the flooding
- highlight differences in flooding mechanisms
- demonstrate that groundwater recharge in response to the July and August flooding events occurred at several sites across the Punjab, particularly in the shallower aquifer

The Pong Dam was crucial in regulating the flow of water during the flooding in July and August, limiting the flow into Punjab and helping avoid significant flooding impacts downstream.

Persistent heavy rainfall during July and August 2023 contributed to elevated soil moisture conditions across both states. These conditions influenced the hydrological response of the region, leading to rapid runoff and severe flooding in Punjab during August 2023. Thus, floods in August were significantly influenced by the antecedent rainfall events in July.

Our results highlight the resurgence of prolonged heavy rainfall events in the Beas Basin and increasing intensity of single-day rainfall events, both of which will amplify flood risk in the future. Our analysis also illustrates that improved rainfall monitoring and better prediction in ungauged regions are important areas of future research.

Flood-induced recharge from the events that occurred in July (pluvial induced) and August (river-flood induced) did not alter longer term trends of stable or declining groundwater levels. Overall monsoon precipitation in 2023 did not deviate significantly from the long-term annual average. Long-term changes in monsoon precipitation may therefore be more important for groundwater recharge than extreme events, but further long-term monitoring is required to confirm.

Our study also indicates that better optimisation of dam operation during flooding might form an important component of an integrated surface and groundwater management approach, including to enhance groundwater recharge. Further research on this is warranted.

Flooding did not appear to have a long-lasting effect on groundwater quality. Future research is needed to investigate the short-term flooding impacts on groundwater quality in this region. Data collected as part of this study can be used to help establish a chemical baseline and, if combined with rapid groundwater-quality investigations after major flooding events, can offer more responsive and timely insights in future.

1 Introduction

On 9 July 2023, intense rainfall led to severe flooding in the mountainous state of Himachal Pradesh (HP) in northern India. Rainfall on that date was roughly 400% above average daily monsoon precipitation. This initial flood event was followed by further flooding in mid-August 2023. Flooding also occurred in Punjab, the neighbouring downstream state, during this period. Despite these significant flooding events, overall monsoon rainfall for the 2023 summer monsoon did not deviate significantly from historical monsoon totals.

Our overall aim was to understand the flooding mechanisms and impacts on groundwater in north-west India. However, this study also contributes to address gaps in understanding around effects of climate change in highland areas and the implications this has for downstream water resources. It is important to understand the evolving characteristics of flooding in the face of climate change, particularly in highly vulnerable regions such as the Himalayas. Improved understanding of flood processes is important to help improve flood prediction, early warning and flood risk management in these regions. Furthermore, the water security implications of floods, like those that occurred in July and August 2023 in HP and Punjab, have potentially important consequences for regional food security and community resilience because of the importance of the groundwater for irrigation in Punjab, which is the regional breadbasket.

Punjab is a highly productive agricultural area largely because of the ability of farmers to easily access groundwater. As a result, groundwater is overexploited and has undergone significant depletion in the last two decades: some estimates indicate that up to 70 km³ of groundwater was lost between 2000 and 2010 (for example, MacAllister et al. (2022)). Furthermore, intensive agriculture severely impacts groundwater quality as fertilisers and other pollutants infiltrate the groundwater. The scale of the successive floods during the 2023 summer monsoon provided a unique opportunity to investigate the role of flooding in counterbalancing groundwater depletion and in mobilising a range of contaminants, including those with implications for agricultural activity (for example, organic contaminants). Understanding the role of flooding in groundwater recharge in this region will provide useful insights for other agriculturally important but environmentally delicate and highly vulnerable regions around the world in the context of a globally changing climate.

The specific aim of this project was to constrain the scale of the extreme flood events that occurred in HP and Punjab in July and August 2023 and to assess the cumulative impact of continued heavy rain and flooding from the 2023 monsoon, focusing on groundwater recharge and contamination.

The objectives were:

- characterise initial flood dynamics and cumulative impacts of persistent rain using post-flood surveys, remote sensing and modelling to estimate flood inundation, peak flow, magnitude and the role of water management structures such as dams in the mountains and plains
- collect and interpret groundwater level and natural tracer data to quantify the impacts of floods on groundwater levels and recharge in the Punjab plains, and to relate this to upstream and downstream flood characteristics
- quantify flood impacts on water quality by collating baseline data and conducting new groundwater quality sampling and analysis in Punjab

2 Objectives

The study region includes the mountainous areas of Manali-Kullu-Mandi in HP and the agriculturally productive Punjab regions of Bist-Doab and Malwa in the plains (Figure 1). The objectives were achieved via three technical work packages and one consolidation and engagement work package. Each work package was linked. Data collection for each work package took place in parallel and was conducted by two teams — one in HP and the other in Punjab — with support from BGS in the UK. Findings from each work package informed analysis in the others; this is particularly true of objectives 1 and 2, where flood modelling was used to identify areas inundated during the flooding that contextualised the interpretation of the groundwater level data.

Outreach activities consisted of stakeholder engagement to inform an overarching analysis of the findings from each of the other three objectives. Additional activities included dissemination of the results via workshops, conference presentations and articles.

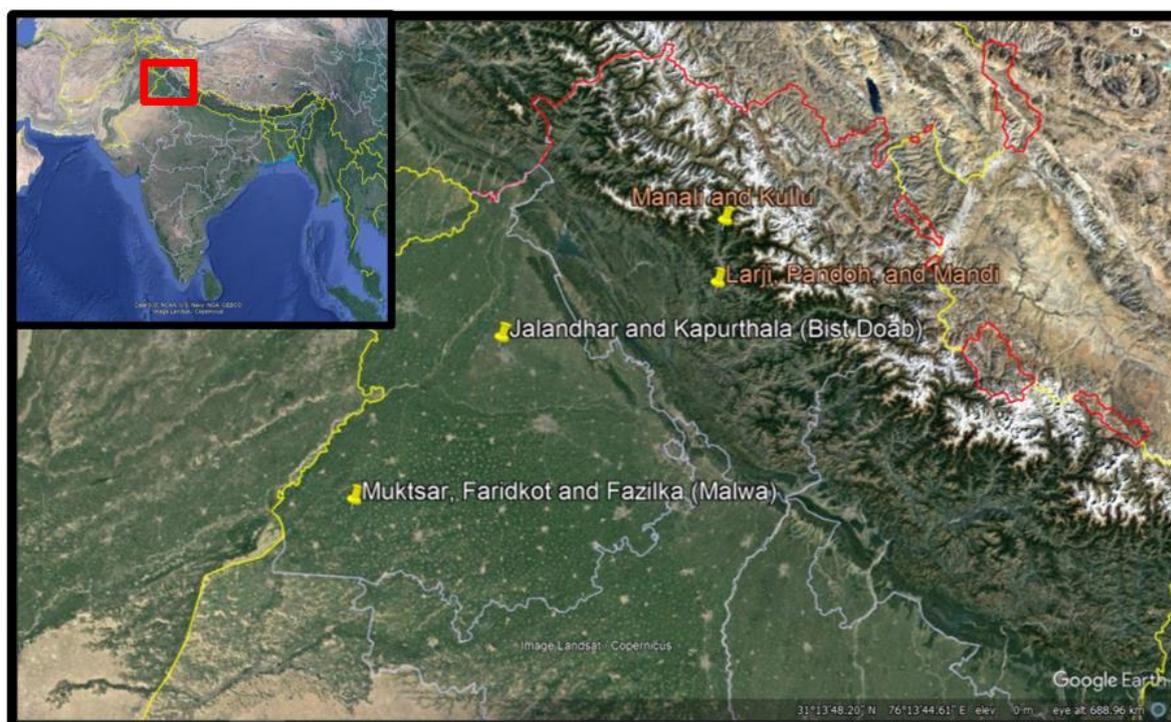


Figure 1 Locations of the study areas in Punjab (text in white) and Himachal Pradesh (text in orange). The inset map with the red box shows the location of Punjab and Himachal Pradesh in north-west India. Map and inset data: Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Image Landsat/Copernicus, Google Earth 2025.

2.1 OBJECTIVE 1: FLOOD CHARACTERISATION

The objective of this work package was to characterise the initial flood event in July 2023 and subsequent heavy rainfall and flooding in the study area to develop hydrologic-hydraulic models targeted on our study areas (Figure 1) in both the mountains and plains.

Post-flood trash line surveys, in conjunction with remote sensing imagery, were to be used to map flood impacts in upstream and downstream areas. Elevation models, derived from high-resolution satellite imagery for key time periods (identified from the hydrological response), coupled with mapped flood extents, were used to provide an understanding of the flood volume and flow pathways. This collated data was then used to inform one-dimensional and two-dimensional Hydrologic Engineering Center River Analysis Software (HEC-RAS) steady and unsteady flow models.

The flood characterisation was used to help understand groundwater recharge dynamics and distribution of flood related contamination, which are the focus of objectives 2 and 3 respectively.

The data collected for this objective includes:

- trash-line surveys and alternative datasets, such as river stage levels, to map the maximum flood extent and estimate peak flow
- remote-sensing data: a systematic evaluation of multiple openly available digital elevation model (DEM) products was undertaken and remote sensing imagery from the Sentinel-1, Sentinel-2 and Landsat satellites was used over a period of approximately two months to analyse the flood inundation in Punjab
- HEC-RAS models of the Beas River, which allowed for comparative analysis of the managed and unmanaged-dam scenarios at the Pong Dam
- evaluation of the impact of dam operations during the August 2023 flooding events

Drone-acquired cross-sectional data was initially planned to provide spatially continuous measurements of channel geometry. However, the study adopted a more comprehensive approach by conducting a systematic evaluation of multiple openly available DEM products. This change in methodology was advantageous, as it enabled a broader spatial coverage and allowed for comparative assessment of various high-resolution terrain datasets.

Questionnaires and data collected by flood responders were initially planned to collect information about the cumulative flood impact, including damage extent, peak water levels, duration of flooding, depth of flooding, perception of peak flow and sequence of events. These were not conducted, as the project team felt their utility in model development and calibration was limited. However, stakeholders were actively engaged throughout the project.

2.2 OBJECTIVE 2: ASSESSING GROUNDWATER LEVEL RESPONSES TO FLOODING

This work package sought to describe the cumulative impact of flooding on groundwater recharge in the Punjab plains.

Many districts of Punjab were reported to be waterlogged for several days following the floods. Surplus runoff and water ponding can lead to enhanced groundwater recharge, so natural tracers and groundwater level data were collected and interpreted, considering the flood extent and hydrological characterisation conducted in Objective 1 to investigate the source and spatial and temporal extent of flood-related groundwater recharge.

The data collected included:

- groundwater level data collected from existing monitoring stations and compared to pre-flood data to assess recharge due to recent flooding in relation to baseline conditions
- natural and environmental tracer data from surface water in the HP and groundwater in Punjab to assess groundwater recharge, including measurement of stable isotopes of water ($\delta^{18}\text{O}$ and δD), SF_6 , chlorofluorocarbons (CFCs) and ^3H .
- existing baseline groundwater isotope data from shallow (less than 30 m) and deep (more than 30 m) boreholes, allowing for an assessment of the depth of contaminant infiltration in the regional aquifer system (this data was used for comparison with isotope data collected during the project and likely to have been impacted by flooding)

The original intention was to collate hydrogeological property data to complement the groundwater level time series, but the data was not deemed to add substantial value to the project and was therefore not included.

2.3 OBJECTIVE 3: ASSESSING GROUNDWATER QUALITY IMPACTS

The objective of the third work package was to quantify the impact of the 2023 flooding on shallow and deep groundwater quality. Existing baseline water quality data was compared with new water quality data, with an emphasis on contaminants with implications for human health.

The data collected for this objective included:

- water chemistry samples focusing on ion chemistry and pesticides, which are typically found at much higher concentrations in surface waters (Ascott et al., 2016; Li et al., 2014), so are indicative of flood contamination; they also have implications for human health
- existing baseline groundwater-chemistry data and data on SEC from shallow (less than 30 m) and deep (more than 30 m) boreholes allowing for an assessment of depth of contaminant infiltration in the regional aquifer system. This data was used for comparison with ion chemistry and SEC data collected during the project from sites likely to have been impacted by flooding
- indicators of microbial contamination: samples for fluorescence analysis were collected as a good indicator of overall risk of microbial contamination in shallow aquifers (Ward et al., 2021)

Initially, microbiological sampling was planned as an indicator of surface water ingress to aquifers because it is suggestive of rapid pathways during flooding and after intense monsoon rains (Gowrisankar et al., 2017) and has impacts on human health. However, fieldwork was started several months after the flooding events and, due to the relatively short survival times of microbes in groundwater (in the range of days to weeks (John et al., 2005)), it was considered that too much time had elapsed for any results of viable microbes (for example, thermotolerant coliforms) to be indicative of the flood events. Therefore, this sampling was not undertaken and was replaced by fluorescence analysis of water samples.

2.4 OUTREACH ACTIVITIES: CONSOLIDATING EVIDENCE, STAKEHOLDER ENGAGEMENT AND PATHWAYS TO IMPACT

The objective of outreach activities was to involve stakeholders at both the early and late stages of the project as a two-way dialogue. Meetings and workshops were intended to inform project planning and views were sought on participants' perception of the flooding and groundwater-related challenges in HP and Punjab, and to feed back and discuss the findings of the study.

Stakeholder engagement was conducted via:

- a project initiation meeting to ensure stakeholders' needs were addressed from the outset of the project, and for input to help inform the methodological design of the project
- activities such as data sharing and input to help inform site selection and analysis on an ongoing basis throughout the duration of the project
- a mid-term update to present initial results and provide an opportunity for stakeholder feedback and input to help calibrate the approach to ensure it was continuing to meet stakeholders' needs
- a final project workshop to present the consolidated results to the widest possible array of stakeholders and identify avenues for wider dissemination of the results

3 Methods

3.1 FLOOD CHARACTERISATION

3.1.1 Trash line surveys and river stage data

During the post-flood investigation, trash-line surveys were conducted at various locations along the river reach. However, traditional high-water marks and flood markers were not identifiable during the field visits due to the elapsed time between the flood event and the survey period. Alternative data sources were successfully used for model calibration. Specifically, hourly river-stage data obtained from the Jal Shakti Vibhag at the Mandi location proved important in determining the high flood levels. This continuous time-series data provided a reliable basis for model calibration, ensuring the accuracy of the hydraulic analysis despite the challenges in physical flood-marker identification.

3.1.2 Remote sensing data

While initial plans included drone surveys, the study adopted a more comprehensive approach by conducting a systematic evaluation of multiple, openly available DEM products. This change in methodology was advantageous as it enabled a broader spatial coverage and allowed for comparative assessment of various high-resolution terrain datasets.

Through rigorous spatiotemporal validation, the most suitable DEM ([Copernicus](#)¹) was identified based on its accuracy and resolution for simulating flood extent and depth. The selected dataset demonstrated robust performance in scenario-based analysis, enabling detailed flood inundation modelling across the entire study area. This approach not only ensured the reliability of the hydraulic modelling results but also provided a more extensive and systematic terrain analysis than would have been possible with localised drone surveys.

To analyse the flood inundation in Punjab, remote sensing imagery from the Sentinel-1, Sentinel-2, and Landsat satellites was used over a period of approximately two months. The objective was to assess the spatial extent of flooding and validate the results of the flood model. The analysis provided critical insights into the accuracy of the model by comparing observed inundation patterns with simulated outputs. The integration of multi-sensor satellite data enabled a comprehensive evaluation of flood dynamics. Additionally, the study facilitated the identification of suitable water sampling sites in Punjab, ensuring a strategic approach to post-flood water sampling.

Raw, synthetic aperture radar (SAR) images typically depict water surfaces as black because of specular reflection from smooth water, which directs radar energy away from the sensor. Sentinel-1 SAR data was filtered for interferometric wide swath mode with vertical-horizontal polarisation and descending orbits at a 10 m resolution. To cover the entire state, mosaics were created by combining images taken on separate dates. For the July flood, images from 5 and 12 July were mosaicked; for August, mosaics from 10 and 17 August, as well as 22 and 29 August, were produced. Speckle noise was reduced by applying a focal mean filter and a ratio image was calculated by dividing post-flood by pre-flood images. Thresholding, one of the most frequently used segmentation methods, was used in image processing. A difference threshold of 1.35 was applied to identify pixels with significant backscatter changes, indicative of inundation. To refine the flood extent, areas of permanent water (such as Ranjit Sagar, Maharana Pratap Sagar/Pong Dam and Govind Sagar) were masked using the Joint Research Centre [Global Surface Water](#)² 'seasonality' layer and connectivity filters were applied to remove isolated noise. Additionally, steep areas (slope more than 5 per cent) were excluded using a DEM-derived slope map.

¹ <https://spacedata.copernicus.eu/en/web/guest/collections/copernicus-digital-elevation-model>

² <https://publications.jrc.ec.europa.eu/repository/handle/JRC109054>

3.1.3 Flood modelling and evaluation of dam operations

Two-dimensional hydrodynamic modelling using HEC-RAS was conducted by employing the rain-on-grid (RoG) approach for flood inundation analysis. The modelling study area covered the Beas River extending to its confluence with the Sutlej in Punjab, with a refined mesh structure of 10 m resolution in the main channel areas to enhance simulation accuracy. Copernicus DEM of 30 m resolution was used for terrain representation and European Space Agency Sentinel-2 derived land use/land cover data for distributed Manning's roughness coefficients. Daily outflows from the Pong Dam (provided by BBMB) were used as boundary conditions to simulate the floods in the river. ERA-5 hourly precipitation data was also incorporated as meteorological input to simulate the RoG-based inundation. The model setup allowed for comparative analysis of managed-dam and unmanaged-dam scenarios to evaluate the impact of dam operations during the August 2023 flooding events, with the computational domain spanning approximately 4398 km² and utilising over 2 million mesh elements for precise hydraulic calculations. The flooding conditions simulated using the HEC-RAS model were compared with Landsat 9 images to assess the extent of inundation during the flood event.

To evaluate dam operations, a reservoir release strategy was developed using a genetic algorithm (GA) integrated with a piecewise penalty function. GAs find the best possible solution to a problem by mimicking the process of natural selection and evolution. Instead of trying every single possibility, it 'evolves' a good solution from a population of potential but random solutions. The GA utilised inflow forecasts derived from the Soil and Water Assessment Tool model to optimise reservoir operations from 1 to 20 of August 2023.

Reservoir operation involves managing trade-offs between conflicting objectives. A primary objective is to regulate releases to reduce downstream flood risk during periods of extreme inflow. At the same time, it is essential to retain enough storage to secure future water demands, including domestic water supply and hydropower generation. In our GA framework, these trade-offs were captured through two objective functions: to reduce downstream flood risk by minimising peak outflows and to maximise storage to maintain reliable water availability. These objectives were achieved in compliance with the reservoir mass balance equation and operational release constraints.

A piecewise penalty function encodes operational realism by sharply penalising the constraint violations, such as overtopping maximum reservoir limits. The framework provides the optimum release strategy daily after updating inflows and storage with observations. Multiple simulations were conducted based on our framework under different maximum reservoir stage limits to examine alternative operational scenarios and their potential outcomes.

The HEC-RAS flood inundation maps served as the basis for population exposure analysis during the flooding. Inundation extents were overlaid with village-level demographic data from the 2011 census of India to assess population vulnerability. Population within each village was assumed to be uniformly distributed and areas within inundated zones were considered exposed to flooding.

Population vulnerability was assessed using multiple categories, including:

- total population, representing overall community exposure
- total male and female populations
- children aged 0 to 6 years
- total working population, disaggregated by gender
- non-working population, disaggregated by gender

3.2 GROUNDWATER LEVEL OBSERVATIONS

Raw groundwater level data was obtained from Punjab WRD (n=130) and CGWB (n=169). WRD data was collected every 15 minutes between January 2023 and September 2024, allowing for the flood signature to be identified visually. CGWB data was recorded approximately four times a year from 2013 to 2023, including data collection pre- and post-monsoon, allowing the higher temporal resolution but shorter time series WRD data to be

contextualised. Only those time series from CGWB sites with time-series data that covered the 2023 flooding events were used in the analysis.

For both datasets, data processing and quality assurance were applied to identify those time series that could provide reliable information. Common error correction, such as adjustments for step changes when the data sensor might have shifted, were applied based on expert judgement. However, those time series with either insufficient data to obtain good information about the groundwater level response to the 2023 flooding events or those with long data gaps or errors that could not be corrected unambiguously were excluded from data interpretation. A summary of data used in the analysis is provided in Table 1.

Table 1 Collected and analysed groundwater level data by data provider and district.

| Data | Jalandhar (Bist-Doab) | Kapurthala | Bathinda (Malwa) | Faridkot | Fazilka | Mukatsar | TOTAL |
|----------------|--------------------------|------------|---------------------|----------|---------|----------|------------|
| WRD-collected | 56 | 31 | 0 | 9 | 19 | 15 | 130 |
| WRD-analysed | 50 | 29 | 0 | 7 | 15 | 15 | 116 |
| CGWB-collected | 0 | 0 | 6 | 43 | 72 | 48 | 169 |
| CGWB-analysed | 0 | 0 | 0 | 24 | 21 | 19 | 64 |

3.3 WATER SAMPLING

3.3.1 Natural and environmental tracers

There is a wide range of natural and environmental tracers that can be used to evaluate surface/groundwater interactions (Kalbus et al., 2006). Stable isotopes of water ($\delta^{18}\text{O}$ and δD) are amongst the most widely used environmental tracers (Krishan et al., 2023) and are suited to examine recent changes in groundwater recharge due to flooding. SF_6 , CFCs and ^3H are commonly used as environmental tracers for dating young groundwater (Krishan et al., 2021; Lapworth et al., 2015).

Groundwater in Punjab is usually recharged either directly through precipitation, or indirectly via canals and rivers, or due to irrigation return flows. Stable and radioisotopes of water can be used to help fingerprint and trace the origin, age and transport of recharging water. SF_6 and CFCs are anthropogenic gases that have been widely used as environmental tracers for dating young groundwater, typically in the age range of 0 to 70 years (Darling et al., 2012; Chambers et al., 2019). These gases were introduced into the atmosphere in the mid-20th century, and their atmospheric concentrations have been well documented over time. When groundwater is recharged, it equilibrates with the atmospheric concentrations of these gases, effectively 'locking in' a time stamp. By measuring the concentrations of SF_6 and CFCs in groundwater samples and comparing them to historical atmospheric records, the time since recharge can be estimated, providing insight into mean groundwater age, flow patterns and recharge rates.

^3H is a naturally occurring, radioactive isotope of hydrogen. Its presence in the atmosphere was significantly increased during nuclear weapons testing in the 1950s and 1960s, creating a well-defined peak in ^3H levels in precipitation. When groundwater is recharged, ^3H from rainfall enters the subsurface, allowing it to serve as a time marker. As with SF_6 and CFCs, the recharge time of the water can be estimated by measuring ^3H concentrations in groundwater.

Stable isotopes were collected (mostly) from surface waters in HP and from groundwaters in Punjab (Figure 2). Tracer samples for groundwater dating (CFCs; SF_6 ; ^3H) were collected and analysed for a subset of groundwater sampling points in Punjab to give an indication of groundwater age. Thirty-six samples for stable isotope analysis were collected in HP in three sampling campaigns that collected data from eight one-off locations in March 2024, 11 sites in May/June 2024 and 17 sites August 2024, of which 11 were a repeat sampling of the May/June campaign. All sampled locations were river samples from the Beas River and its tributaries the

Parvathi River, Sainj River, Tirthan, Uhl, Suketi Khad, Gugli Khad, Nyugal Khad and Shukar Khad, except for one groundwater sample near the Parvathi River and one near Shukar Khad.

In Punjab, 147 groundwater samples for isotope analysis (hand pumps, piezometers) were collected during four rounds of sampling from March 2024 to June 2024 for isotope analysis. A total of 51 samples for CFC measurements and 49 for SF₆ measurements were collected from boreholes and handpumps in Punjab between March and May 2024. The data was complemented with a historic dataset from 2022, which had a partial overlap (26 boreholes for CFC measurements, and slightly fewer for both CFC and SF₆ measurements) with the 2024 dataset. Forty-four groundwater samples were collected in Punjab to be analysed for ³H.

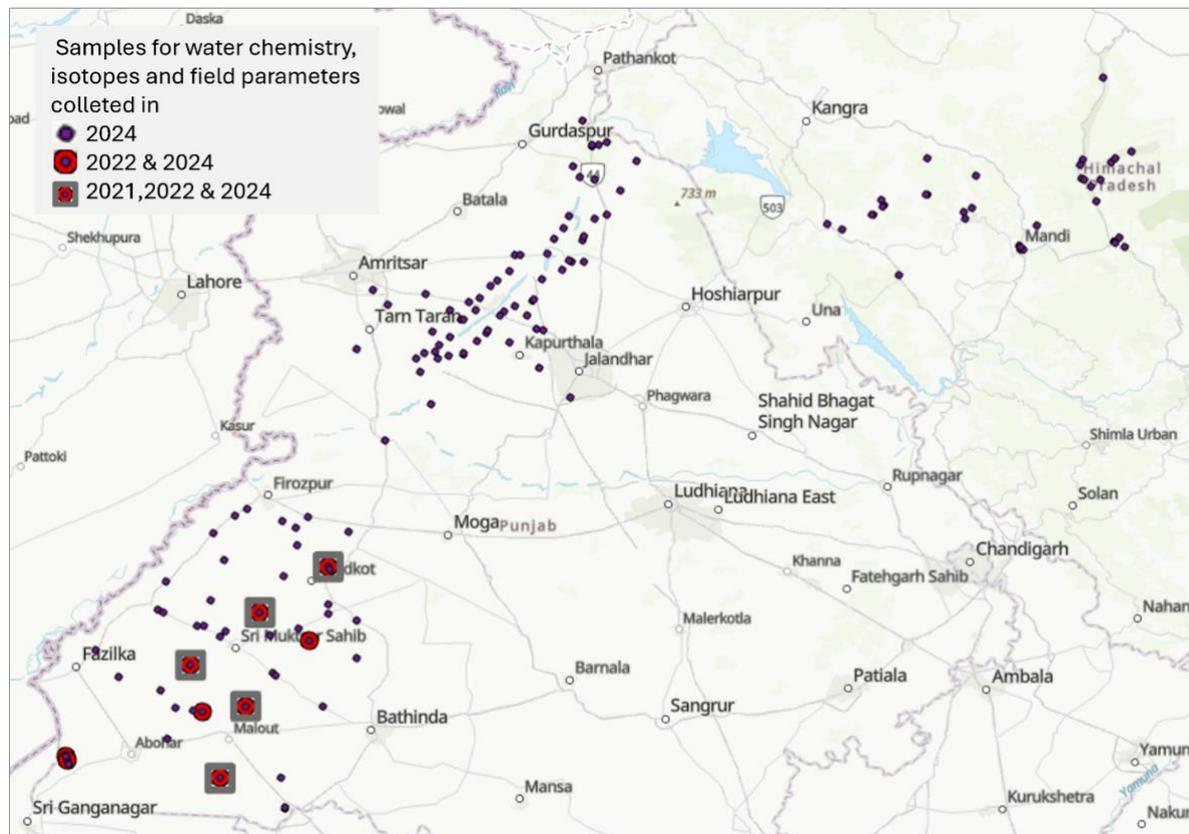


Figure 2 Locations of water samples collected for ion chemistry, stable water isotopes and in situ measurement of field parameters in 2024 (dark purple circles). Sites that were also sampled in previous years are highlighted (red circles in 2022 and again in 2024, and red circles and grey square for sites samples in 2021, 2022 and 2024). BGS © UKRI 2026. Made with Natural Earth vector and raster map data © naturalearthdata.com.

For all groundwater samples, the boreholes or handpumps were purged and samples were collected once field parameters (SEC, pH and dissolved oxygen (DO)) were stable. Surface-water samples were collected as grab samples. Isotope and ³H samples were collected in acid washed low-density polyethylene tarson bottles using the standard methodology. Dissolved gas samples for CFC and SF₆ analysis were collected from boreholes using sealed glass containers in line with the USGS method (USGS, 2021), without exposure to the atmosphere. Samples were only collected where the borehole or handpump infrastructure did not allow for atmospheric contamination via the rising main.

The ratios of heavy stable isotopes ($\delta^{18}\text{O}$ and δD) were measured using a dual inlet isotope ratio mass spectrometer (Isoprime GV instruments, UK) with automatic sample preparation units at the Nuclear Hydrology Laboratory at NIH, Roorkee. For δD analysis, 400 μl of the water sample was equilibrated with hydrogen along with platinum catalyst at 40°C for three hours and the gas was introduced into the mass spectrometer. The $\delta^{18}\text{O}$ of the sample was measured by equilibrating 400 μl of water with carbon dioxide gas at 40°C for seven hours and the

equilibrated gas was introduced into the mass spectrometer. The measured values are reported as delta (δ) values relative to Vienna Standard Mean Ocean Water (VSMOW). CFCs and SF₆ were analysed using gas chromatography (Agilent GC) with electron capture detectors and a bespoke purge-and-trap system (for example, Gooddy et al., 2006) at the BGS laboratory in Wallingford, UK. ³H samples, also analysed by NIH, were distilled to reduce the conductivity; deuterium and hydrogen were removed by the process of physico-chemical fractionation in the ³H enrichment unit, which is based on physico-chemical fractionation by difference in the strength of bonds formed by the light versus the heavier isotope of a given element. Since the observed values of ³H were low, up to ten cycles (runs) were executed using Quintals process. ³H concentration files were created with help of WinQ and Quick start software in Quintals process (liquid scintillation spectrometer). The concentration of ³H in terms of tritium units (TU) of various samples has been determined.

3.3.2 Water chemistry samples

A total of 186 water chemistry samples were collected between March and August 2024. The samples collected for water chemistry were at the same locations as those for isotope sampling (Figure 2). In HP, the focus of the sampling activities was on temporal river water sampling, for which the same sites were sampled in two main campaigns in May/June and August 2024, complemented by a small number of opportunistic samples collected during an initial reconnaissance during the first project meeting in March 2024. In contrast, groundwater sampling was prioritised in Punjab, with a particular focus on the Bist-Doab and Malwa regions. These samples were selected to capture a range of groundwater depths and spatial variation in water quality across both flood-prone and non-flooded areas.

For all groundwater samples, the boreholes or handpumps were purged and samples were collected once stable field parameters (SEC, pH and DO) were reached. Surface-water samples were collected as grab samples. All samples for major ion chemistry were filtered in the field using 0.45 μ m filters and stored in Nalgene bottles. Cation samples were acidified with analytical grade nitric and hydrochloric acids. Field duplicates were taken at selected sites to assess reproducibility. Cations were analysed via ICP-MS (Agilent 8900 Triple Quadrupole), while anions were analysed using ion chromatography (Dionex ICS5000 dual line IC). Most samples were analysed by NIH but a small subset of samples were analysed at BGS in the UK.

3.3.3 Indicators of microbial contamination

Samples for fluorescence analysis have been shown to be a good indicator of overall risk of microbial contamination in shallow aquifers (Ward et al., 2021). Fluorescence can be a good tool for detecting microbiological contamination because many biological substances and microbial byproducts fluoresce under specific wavelength excitation, allowing these substances to be identified by proxy. For example, tryptophan-like fluorescence (TLF) has been associated with microbial metabolism and fresh organic matter, with high levels of TLF usually suggesting recent faecal contamination or active microbial growth (Sorensen et al., 2020). Humic-like fluorescence is mainly derived from decayed organic matter but also correlates with bacterial communities in some cases. The analysis also quantifies different sources of organic carbon, including more labile sources from surface water (Wilson et al., 2023) and contaminants mobilised by flooding to trace flood-related recharge.

Fluorescence samples were taken at 14 locations in HP and 25 locations in Punjab between April and June 2024 (Figure 3). The 14 HP (and additional three sites) were sampled again in August 2024 to identify temporal changes. Fluorescence samples were analysed using emission excitation matrices (EEMs) using a Varian™ Cary Eclipse fluorescence spectrometer at the BGS laboratory in Wallingford in the UK.

Inspection of the fluorescence EEMs revealed the protein-like tyrosine and tryptophan-like, fulvic-like and humic-like components to produce the main peaks in the dataset. TLF intensities were calculated as the mean values from the region Ex270 nm, Em330–350 nm, while fulvic-like (FA) intensities were taken as the mean from Ex330 nm, Em410–440 nm. Results for intensities are reported in arbitrary units (AU).

Three different fluorescence indices were calculated to provide information of the source of dissolved organic matter (DOM): the fluorescence index (FI), used to explore DOM sources, was calculated as the ratio of emission intensities at 450 nm and 500 nm with an excitation wavelength of 370 nm (McKnight et al., 2001). Additionally, the TLF to FA ratio was used to help distinguish between potential DOM sources, based on characteristic values linked to different source materials (Baker, 2002). A high FI and TLF to FA are indicative of higher microbial vs. terrestrial DOM and of more labile (fresh) protein-like DOM vs. humic DOM, respectively. The humidification index (HX1) was calculated based on Ohno (2002) and can be used as a measure of how humified the DOM in the water samples is.

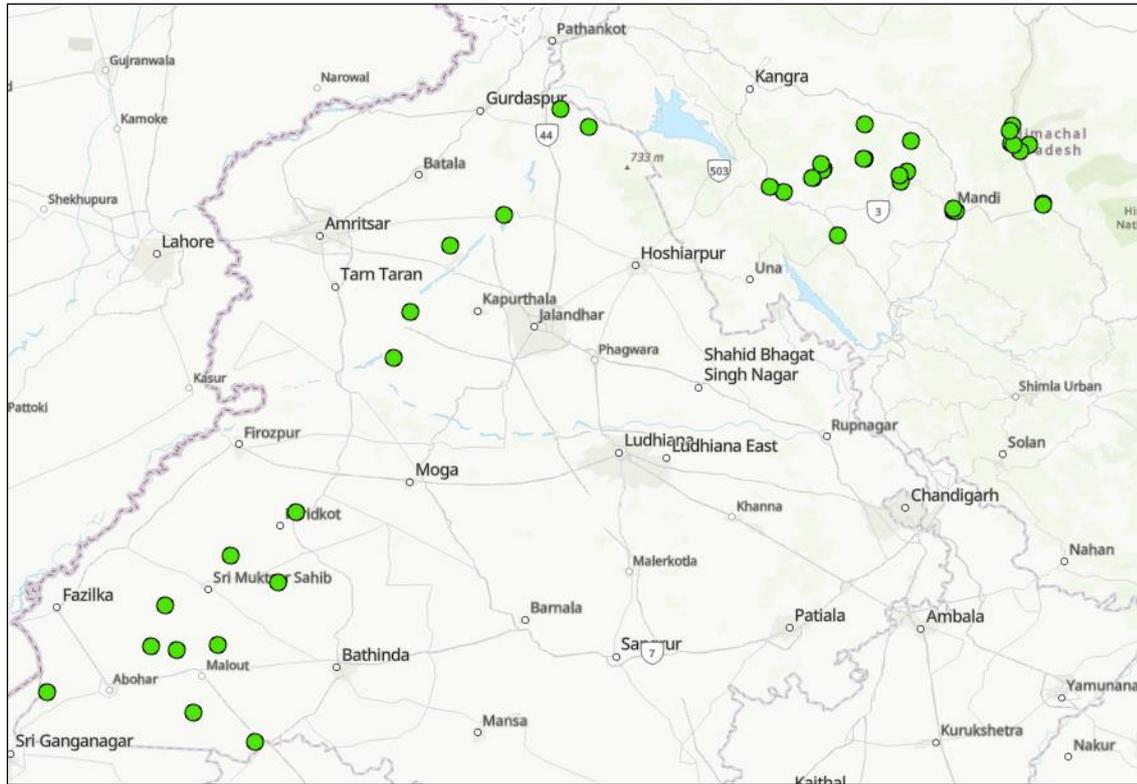


Figure 3 Locations of water samples collected for fluorescence (EEM) analysis. BGS © UKRI 2026. Made with Natural Earth free vector and raster map data © naturalearthdata.com.

4 Results and discussion

4.1 FLOOD CHARACTERISATION

4.1.1 Inundation mapping and hydrometric analysis

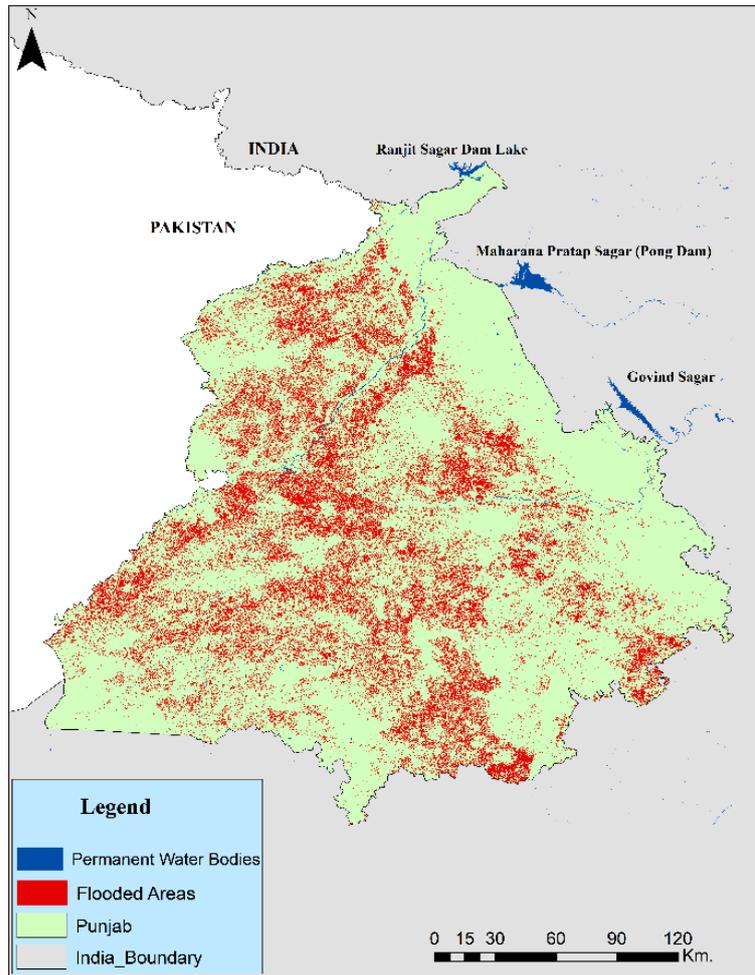


Figure 4 SAR mosaic (5 to 12 July) showing state-level flood inundation with permanent water bodies. © IIT Mandi 2026.

Processed inundation maps derived from remote sensing data and validated by trash-line surveys and river stage data were produced for July and August 2023. The results for July 2023 are depicted in Figure 4. Flood-affected areas are shown in red, while permanent water bodies are rendered in blue, clearly differentiating transient inundation from established water bodies.

In August, the flooding-inundated areas were concentrated along the Beas River basin due to heavy upstream rainfall in HP causing significant amounts of water releases from the Pong Dam (Figure 5). Figure 5a shows SAR-based inundation maps from 10 to 17 August, clearly highlighting flood extents near the Beas-Sutlej confluence. Inundations from 22 to 29 August are shown in **Figure 5b**.

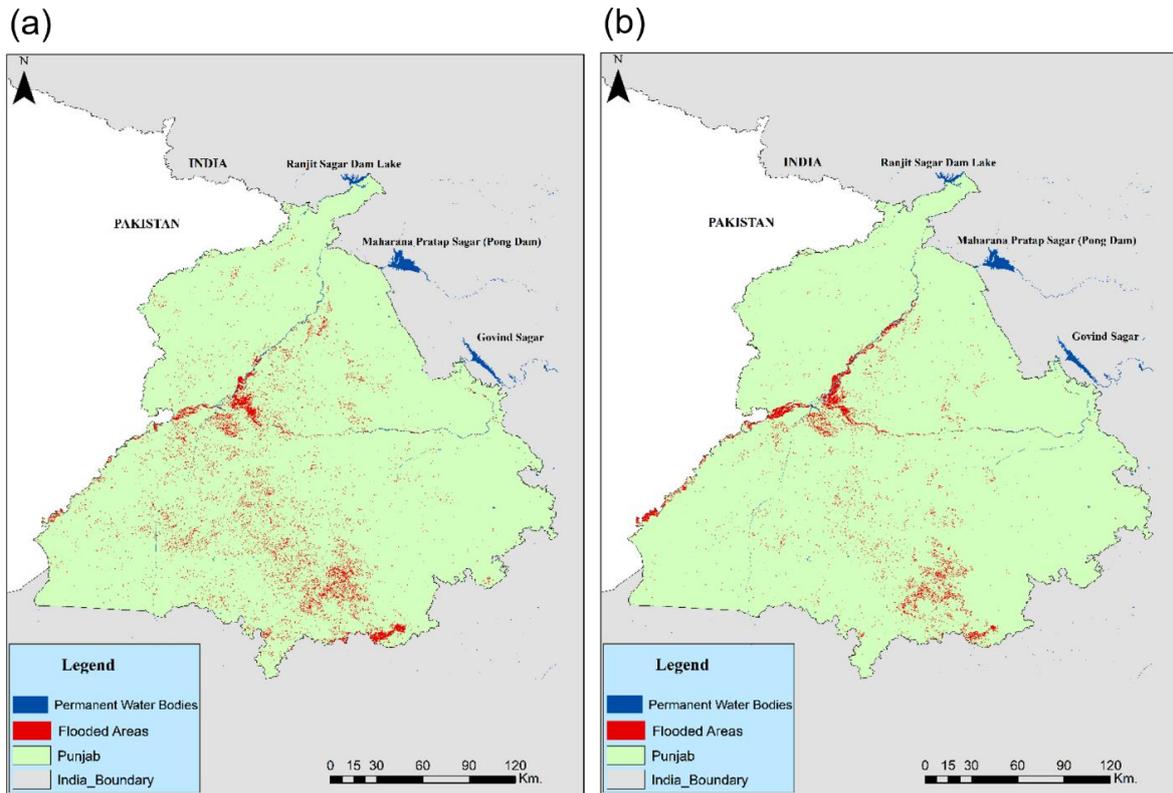


Figure 5 (a) SAR-based inundation map (mosaic from 10 to 17 August); (b): SAR-based inundation map (mosaic from 22 to 29 August). © IIT Mandi 2026.

Hydrometric analysis demonstrated that conditions leading to the severe flooding in Punjab during August 2023 were significantly influenced by antecedent rainfall events in July. A detailed spatial analysis of observed precipitation revealed that, between 9 and 11 July, intense rainfall occurred across both HP and Punjab (Figure 6e). These precipitation events contributed to elevated soil-moisture levels and increased reservoir inflows. Soil-moisture dynamics across the Beas Basin in HP, the Punjab portion of the basin and the rest of Punjab closely followed rainfall patterns during July and August 2023 (Figure 6a, b and c). Surface layers (0 to 10 cm) responded rapidly, with distinct peaks after major precipitation events, whereas subsurface layers (10 to 40 cm and 40 to 100 cm) showed delayed but comparable double peaks. The deepest layer (100 to 200 cm) exhibited a more gradual and lagged response, indicating progressive infiltration and sustained moisture retention at depth.

To have a better understanding, the daily river stage at Victoria Bridge, Mandi, was plotted alongside soil moisture (Global Land Data Assimilation System, GLDAS) at multiple depths and daily precipitation from the India Meteorological Department (IMD) (Figure 6d). These subsurface conditions have influenced the hydrological response of the region, creating a scenario where subsequent rainfall in August was more readily converted into runoff, thereby amplifying the severity of the flooding events.

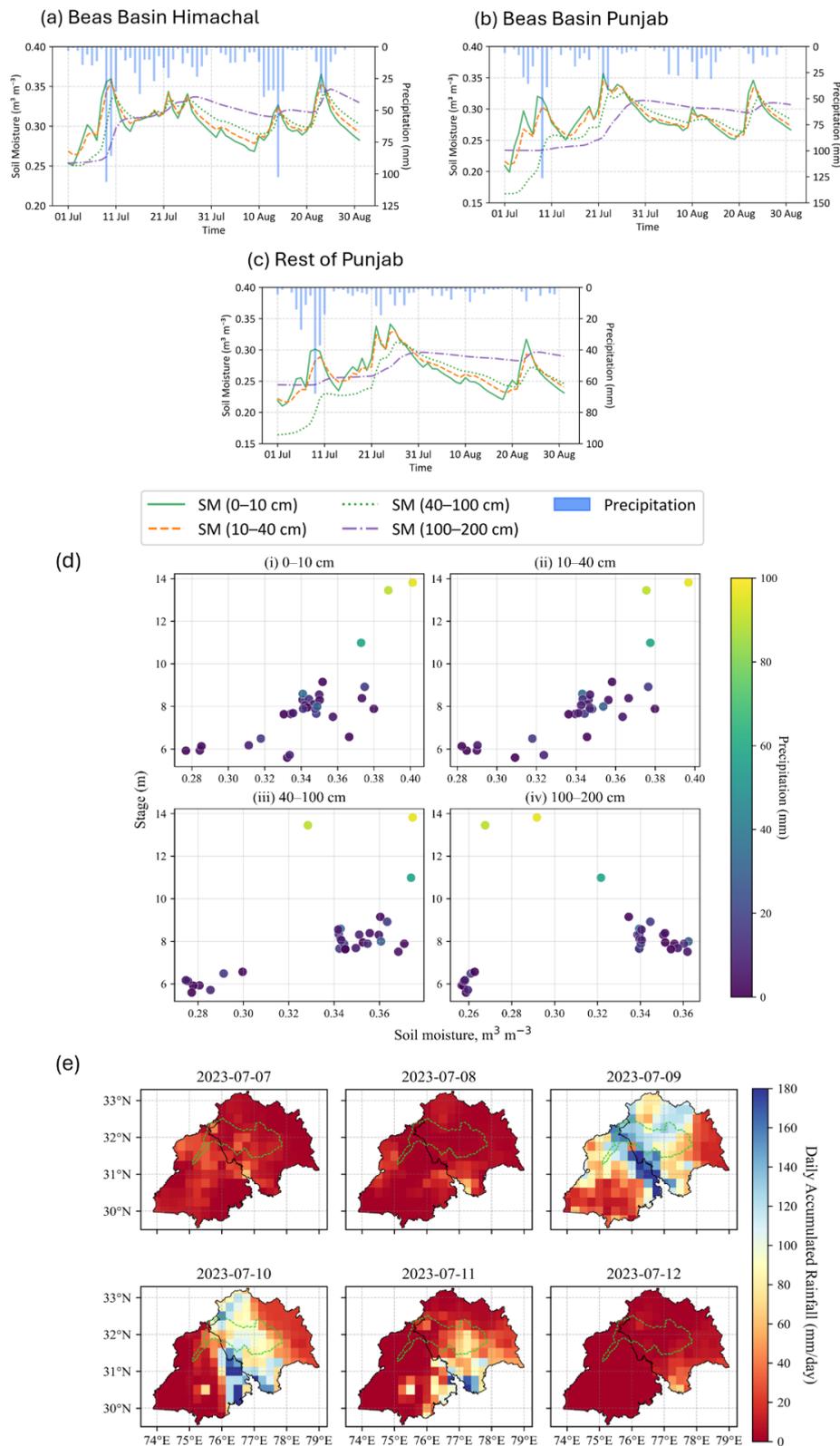


Figure 6 Temporal variations of GLDAS soil moisture ($\text{m}^3 \text{m}^{-3}$) at four depths (0 to 10 cm; 10 to 40 cm; 40 to 100 cm; 100 to 200 cm) across (a) the Beas Basin in Himachal Pradesh; (b) the Beas Basin in Punjab; (c) the remaining parts of Punjab. (d) Daily river stage at Victoria Bridge, Mandi, as a function of GLDAS soil moisture at the same four depths for July 2023, with the colour of the scatter points representing the corresponding daily precipitation at Mandi. (e) Spatial distribution of observed daily precipitation over Punjab and HP from 7 to 12 July 2023. The black outlines mark the state administrative boundaries and the inner green boundary delineates the Beas River Basin, spanning both states. Reproduced from Pathania et al. (2026). © 2025 Elsevier B.V.

Following these precursory conditions, Punjab experienced two severe flooding events from 15 to 17 August and from 23 to 25 August 2023. The first flooding event was primarily triggered by intense rainfall (102.5 mm) over the Beas River Basin in HP on 14 August (Figure 7a). This excess rainfall over the upstream region resulted in the significant runoff, which travelled downstream to Punjab through the Pong dam. The second flooding event was primarily associated with localised heavy rainfall in regions bordering HP and Punjab and the release of excess runoff from the upstream dams (Figure 7b).

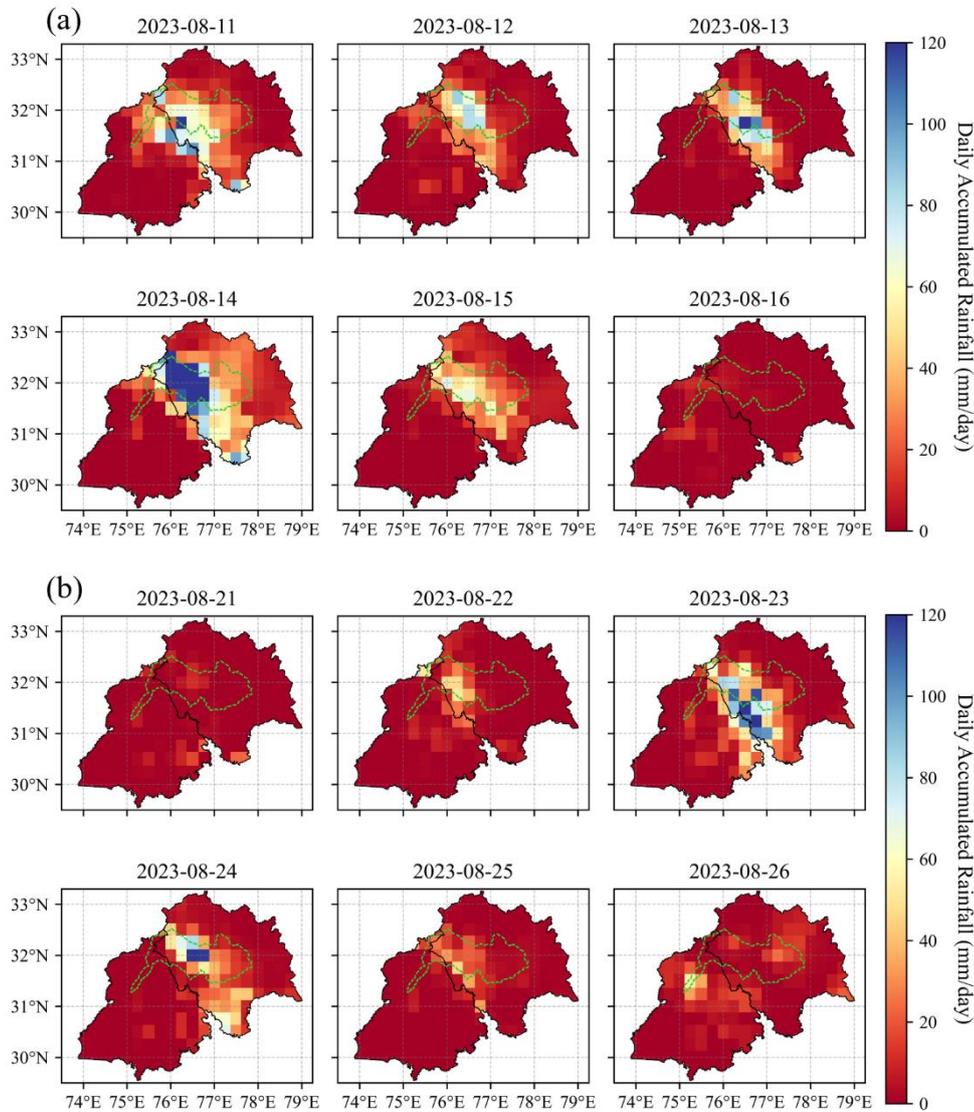


Figure 7 Spatial distribution of observed precipitation. (a) 11 to 16 August (b) 23 to 26 August 2023 over Punjab and HP. The black outlines indicate the administrative boundaries of the two states, while the inner green demarcation highlights the Beas River basin spanning both regions. Reproduced from Pathania et al. (2026). © 2025 Elsevier B.V.

The recurring flood events in the region have been primarily triggered by episodes of extreme precipitation, underscoring the need for a detailed analysis of rainfall extremes to better understand their evolving characteristics and associated flood risks. The analysis of six extreme precipitation indices (R10 mm; R50 mm; R100 mm; R×1 day; R×5 day and Total Precipitation (PRCPTOT), was conducted to evaluate the occurrence of extreme events across the study domain. Decadal mean values from 1980 to 2019 were compared to their occurrences during the recent period of 2020 to 2023 for the three subregions: Beas Basin in HP (BB Himachal), Beas Basin in Punjab (BB Punjab) and the rest of Punjab (Rest Punjab). The radar charts highlight the temporal variations of the extreme precipitation indices (Figure 8).

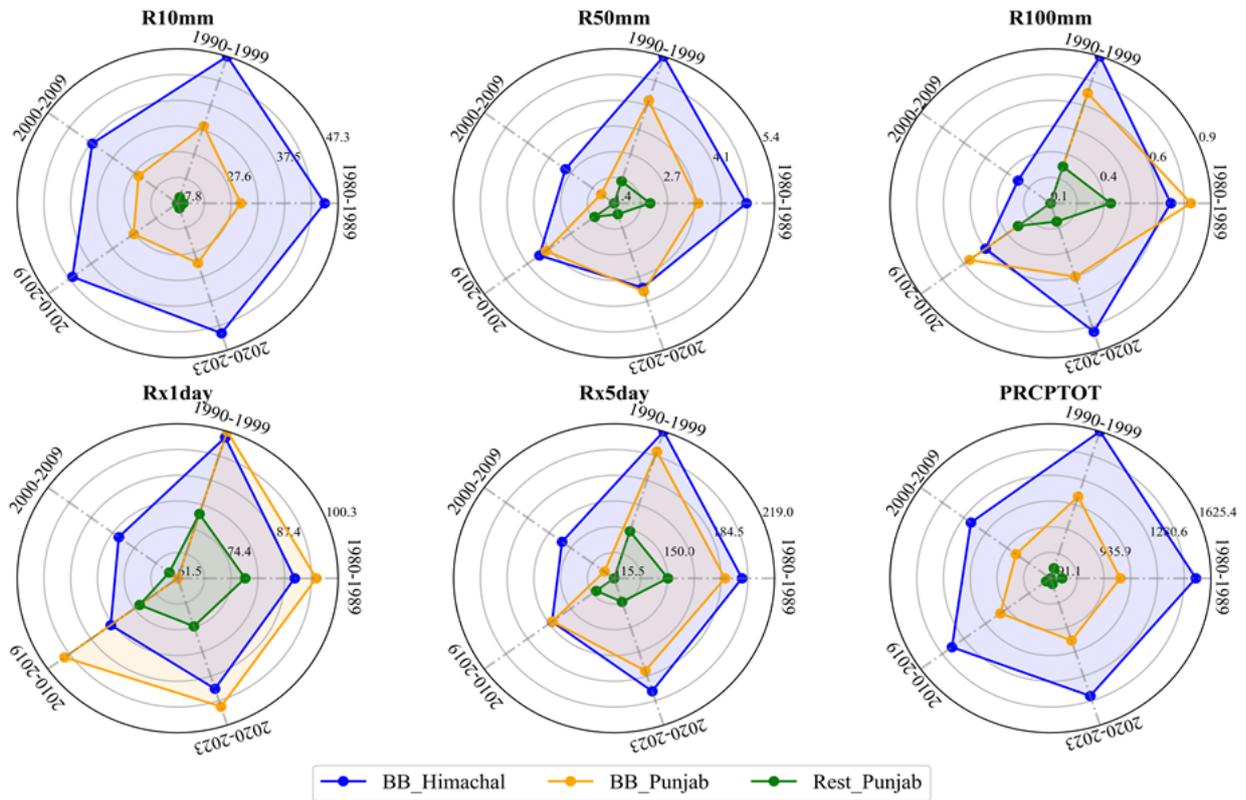


Figure 8 Radar plot of precipitation extremes from 1980 to August 2023. Reproduced from Pathania et al. (2026). © 2025 Elsevier B.V.

The R10 mm index represents the count of annual days with rainfall exceeding 10 mm. In BB Himachal, the R10 mm values peaked at 47.30 days during the 1990s, then declined to 37.25 days in the 2000s. However, a gradual increase is observed in the subsequent decades, with values increasing to 41.72 days in the 2010s and further reaching 43.85 days during 2020 to 2023, indicating a near return to the 1990s levels. Similarly, BB Punjab recorded its highest R10 mm values at 33.27 days in the 1990s, followed by a sharp decline to 26.68 days in the 2000s. Despite a slight improvement in recent decades, with values reaching 29.8 days during 2020 to 2023, the frequency of moderate rainfall events remains below the 1990s peak. For Rest Punjab, the R1 mm values have shown relative stability, with minor fluctuations from 19.05 days in the 1990s to 18.83 days in the 2020s. This consistency indicates limited variability in moderate rainfall events across the region compared to the pronounced trends observed in BB Himachal and BB Punjab.

The R50 mm index, that is the count of annual days with rainfall exceeding 50 mm, shows distinct trends across the study regions. In BB Himachal, values peaked at 5.41 days in the 1990s, declined sharply to 2.94 days in the 2000s and recovered slightly to 3.74 days during 2020 to 2023, though still below the 1990s peak. In BB Punjab, a similar decline from 4.18 days in the 1990s to 1.78 days in the 2000s was observed, followed by a recovery to 3.8 days in the 2020s, nearing 1990s levels. For Rest Punjab, values remained consistently low, declining from 2.26 days in the 1980s to 1.68 days in 2020 to 2023, with minimal variability.

These trends highlight a resurgence of heavy rainfall events in BB Punjab, while BB Himachal shows partial recovery and Rest Punjab remains largely unaffected. The R100 mm index, representing extremely heavy rainfall days exceeding 100 mm, shows notable variations across the regions. In BB Himachal, values peaked at 0.88 days in the 1990s, declined sharply to 0.33 days in the 2000s and partially recovered to 0.78 days during 2020 to 2023. In BB Punjab, a drop occurred from 0.77 days in the 1980s to 0.06 days in the 2000s, with a modest recovery to 0.51 days in the 2020s. For Rest Punjab, values remained low, decreasing from 0.42 days in the 1980s to 0.14 in the 2000s and 0.24 days in the 2020s. These findings align with the

observations of Bhattacharyya et al. (2022), who documented declining trends in R20 mm and R10 mm over the Northern Himalayas from 1986 to 2015.

The R×1 day index represents the maximum daily precipitation across the study area in a given period. It peaks in the 1990s across all regions, with BB Himachal at 98.75 mm, BB Punjab at 100.28 mm and Rest Punjab at 78.51 mm. A sharp decline occurred in the 2000s, particularly in BB Punjab (61.47 mm), followed by recovery in the 2010s and 2020s. Between 2020 and 2023, values rebounded to 90.72 mm in BB Himachal, 95.43 mm in BB Punjab and 74.17 mm in Rest Punjab. This resurgence highlights the increasing intensity of single-day rainfall events, particularly in BB Himachal and BB Punjab, amplifying flood risks.

The R×5 day index denotes the maximum precipitation accumulated over any consecutive five-day period. It peaked in the 1990s, with BB Himachal at 219.04 mm and BB Punjab at 204.81 mm. A sharp decline occurred in the 2000s, reaching 156.96 mm and 123.23 mm, respectively, followed by partial recovery to 195.08 mm in BB Himachal and 180.66 mm in BB Punjab during the 2020s. In Rest Punjab, values remained lower, peaking at 150.18 mm in the 1980s and recovering slightly to 132.05 mm in the 2020s. These trends highlight a resurgence of prolonged extreme rainfall within Punjab, especially in the areas bordering HP and areas contributing to the Beas Basin.

The PRCPTOT index denotes the total annual precipitation on wet days in each period. It peaks in the 1990s, with BB Himachal at 1625.44 mm and BB Punjab at 1165.65 mm. Both regions experienced a sharp decline in the 2000s, followed by partial recovery to 1419.79 mm and 1029.34 mm, respectively, in the 2020s. In Rest Punjab, values remained consistently lower, declining to 591.24 mm in the 2000s and recovering slightly to 631.13 mm. These trends indicate a significant reduction in total precipitation since the 1990s, with a modest recovery in recent years. These results are consistent with the projections of Gupta et al. (2020), who reported an increase in cumulative wet days throughout the 21st century under CMIP6 climate model scenarios.

4.1.2 Assessment and optimisation of dam operations

Assessing dam operation dynamics is critical for understanding dams' influence on downstream flood modulation during extreme hydrometeorological events. On 9 July, BB Himachal reported 106.35 mm of rainfall, while BB Punjab received 126.42 mm and Rest Punjab experienced 68.11 mm. This heavy rainfall spell resulted in a peak inflow of 7328.9 cubic metres per second (cumecs) on 10 July (Figure 9).

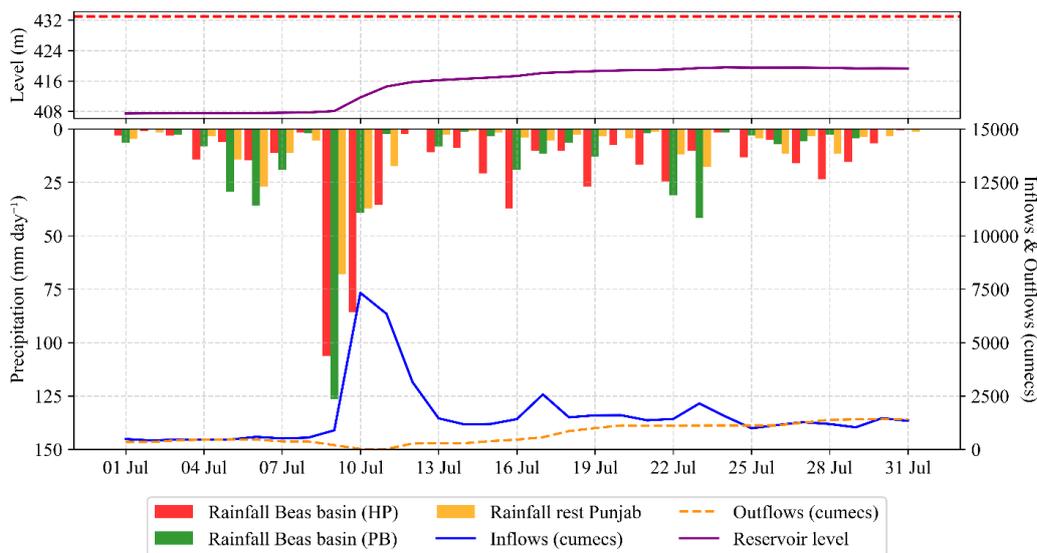


Figure 9 Comparative plot of precipitation with inflows and outflows at Pong Reservoir during July 2023. Reproduced from Pathania et al. (2026). © 2025 Elsevier B.V.

In August 2023, the dam experienced significantly higher inflows due to another spell of extreme rainfall. The observed rainfall values (from IMD) were highest on 14 August 2023, recording 102.52 mm in BB Himachal, 31.11 mm in BB Punjab and 4.17 mm in Rest Punjab. The intense rainfall across BB Himachal resulted in significant inflows into Pong Dam. The total inflow into the dam peaked at 12 469.43 cumecs on 15 August. These high inflows were driven by heavy runoff from BB Himachal following the rainfall on 14 August. Dam outflows were recorded at 499.5 cumecs on 14 August, rising to 2472.6 cumecs on 15 August, 4017.5 cumecs on 16 August and 3679.1 cumecs on 17 August (Figure 10). This gradual release indicates that Pong Dam effectively absorbed the impact of high inflows through a phased water release strategy.

The reservoir levels also reflected the impact of intense rainfall and runoff events. The maximum reservoir level of Pong Dam is 433.12 m and the water levels reached 426.54 m on 15 August, 426.32 m on 16 August and 425.59 m on 17 August. Observed level fluctuations further substantiate that the water release from the dam was regulated and gradual. The study area experienced higher precipitation during July 2023 but, interestingly, the magnitude of dam inflows was higher in August 2023. Thus, the baseline for the August floods was set by the intense rainfall experienced across the study domain in July 2023.

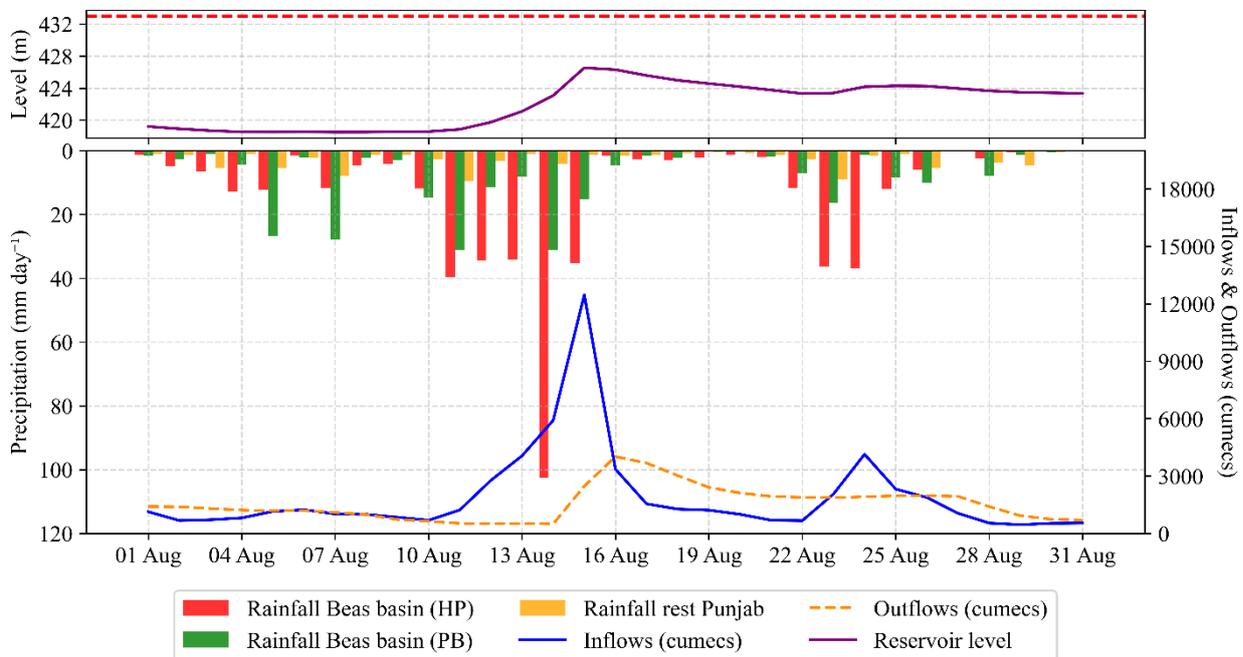


Figure 10 Comparative plot of precipitation with inflows and outflows at Pong Reservoir during August 2023. Reproduced from Pathania et al. (2026). © 2025 Elsevier B.V.

Figure 11 compares observed dam operations and the optimised release scenarios under varying maximum allowable reservoir stage limits. The observed reservoir outflows and stage variations are presented in green, compared against four GA-simulated scenarios. Each scenario follows the same operational and physical constraints, except for variations in the maximum permissible reservoir water level. The stage limits were 419 m, 420 m, 422 m and 424 m. These limits were carefully selected, considering the observed maximum reservoir level reached 426.4 m on 15 August 2023.

The results in Figure 11 highlight the effectiveness of the GA-based release strategies in balancing flood mitigation and water conservation. Peak outflows were effectively reduced in all scenarios, with those having higher stage limits enabling greater water storage within the reservoir. The abrupt changes visible in the proposed release strategies are attributed to the daily updating of reservoir storage using actual inflow values. Figure 11 thus reveals that the

optimised strategies mitigated peak downstream flooding and maintained sufficient reservoir storage for subsequent water demands.

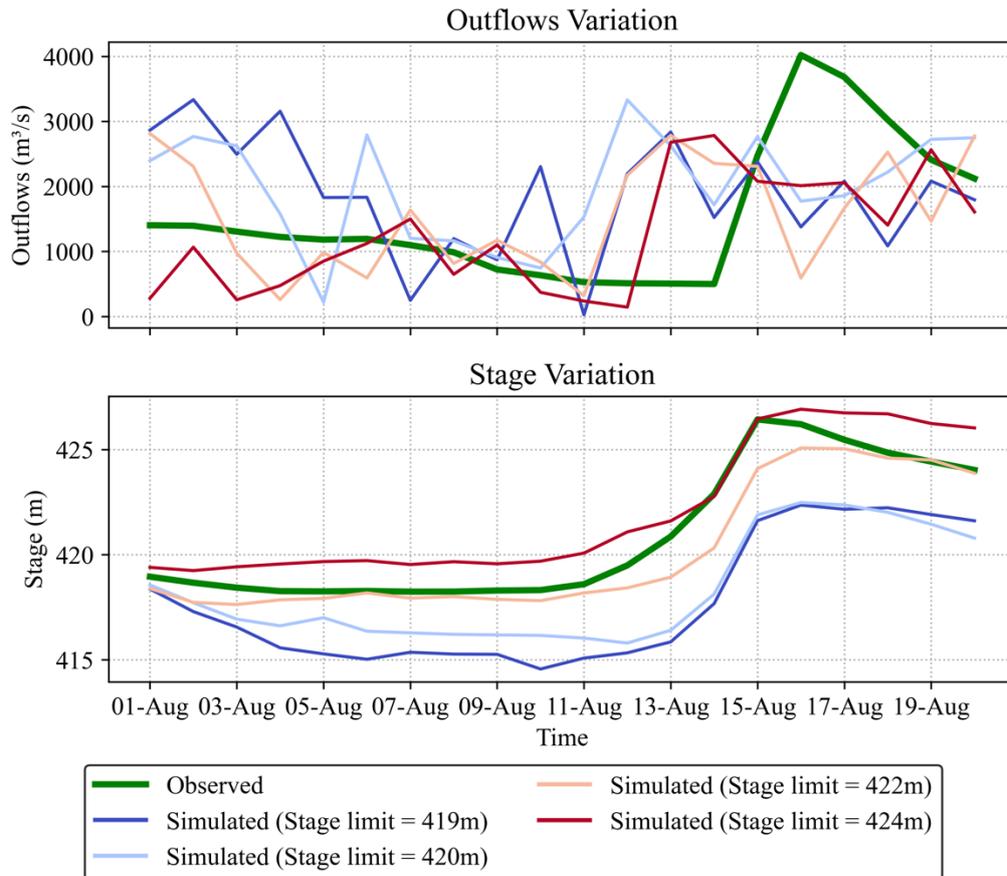


Figure 11 Comparison of observed and GA-optimised reservoir outflows and stage variations under varying maximum stage limits (1 to 20 August 2023). Reproduced from Pathania et al. (2026). © 2025 Elsevier B.V.

4.1.3 Flood modelling and exposure to flooding

Figure 12 compares the observed and modelled pre-flood (3 August) and post-flood conditions (19 August), highlighting the swelling of the Beas River channel and the extent of inundation.

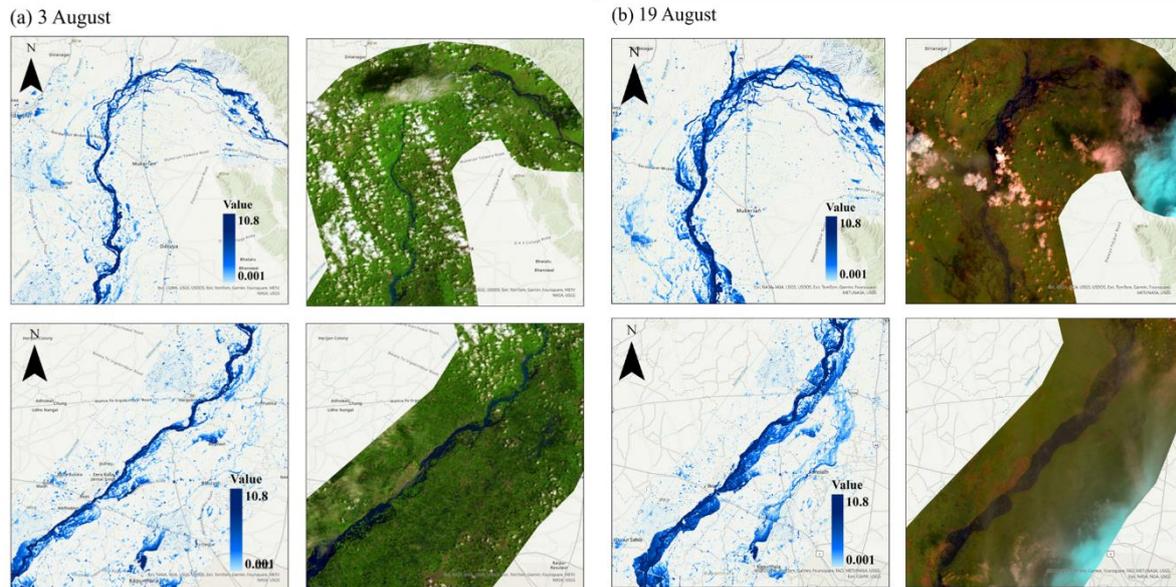


Figure 12 Comparative visualisation of flooding events on (a) 3 August and (b) 19 August between HECRAS and Landsat 9. Reproduced from Pathania et al. (2026). © 2025 Elsevier B.V.

The simulation under actual dam operation conditions indicates that approximately 205 664 individuals were exposed to flooding. In contrast, the unmanaged-dam scenario resulted in an estimated exposure of 367 531 individuals, marking a 78.7% increase in the affected population.

Demographic disaggregation reveals substantial differences in exposure across population segments. Female population exposure would have increased from 98 356 to 175 950 (78.9%) under the unmanaged-dam scenario (Figure 13). Similarly, the number of children aged 0 to 6 years affected would have increased from 23 071 to 42 180, an 82.8% increase. These demographic groups typically exhibit heightened vulnerability to flood-related health risks, mobility constraints and safety concerns.

Socioeconomic analysis further illustrates the differential impacts. The non-working population exposure would have increased from 134 437 to 241 721, a 79.9% increase. Within this category, non-working females would have experienced an 81% increase in exposure, highlighting the intersection of gender and economic vulnerability factors.

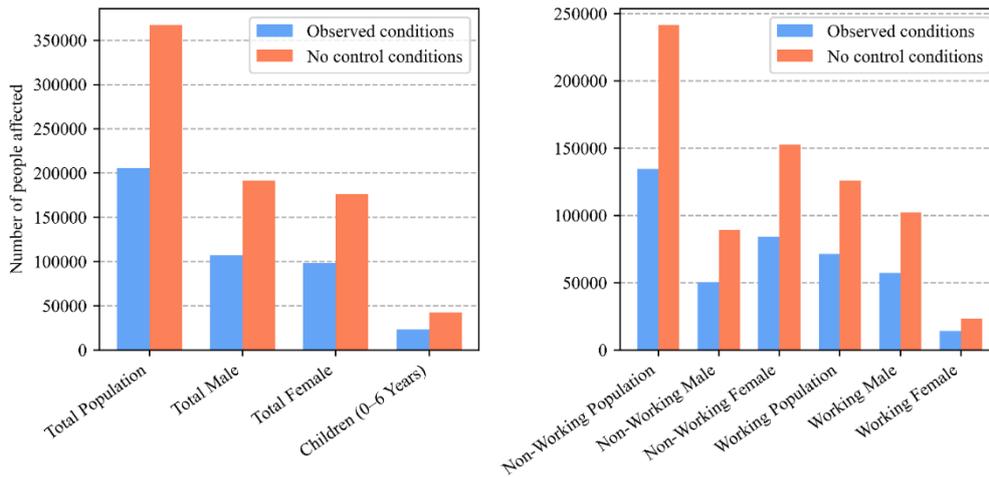


Figure 13 Comparison of flood impact under observed and no-control conditions on 16 August 2023. Reproduced from Pathania et al. (2026). © 2025 Elsevier B.V.

4.2 ASSESSING GROUNDWATER LEVEL RESPONSES TO FLOODING

4.2.1 Groundwater level observations

Based on visual inspection of the WRD data, it was determined that 69% of the 116 analysed groundwater level time series showed a response (water level increase) to the flooding events of July and August 2023 (Figure 14). There was no information supplied on whether any of the monitoring sites are confined aquifers, but further analysis on responses by groundwater level by depth (categorised by site based on median groundwater levels) was undertaken; it indicated that sites with deeper groundwater levels were typically less responsive to the two events (see Figure 14b to e).

The percentage of sites with groundwater level responses to the flooding events was lower in the Bist-Doab (62%) than in the Malwa region (84%). This is likely related to the much higher percentage of locations with median groundwater level depths of more than 20 m below ground level (mbgl) in the Bist-Doab compared to the Malwa region (71% and 5%, respectively).

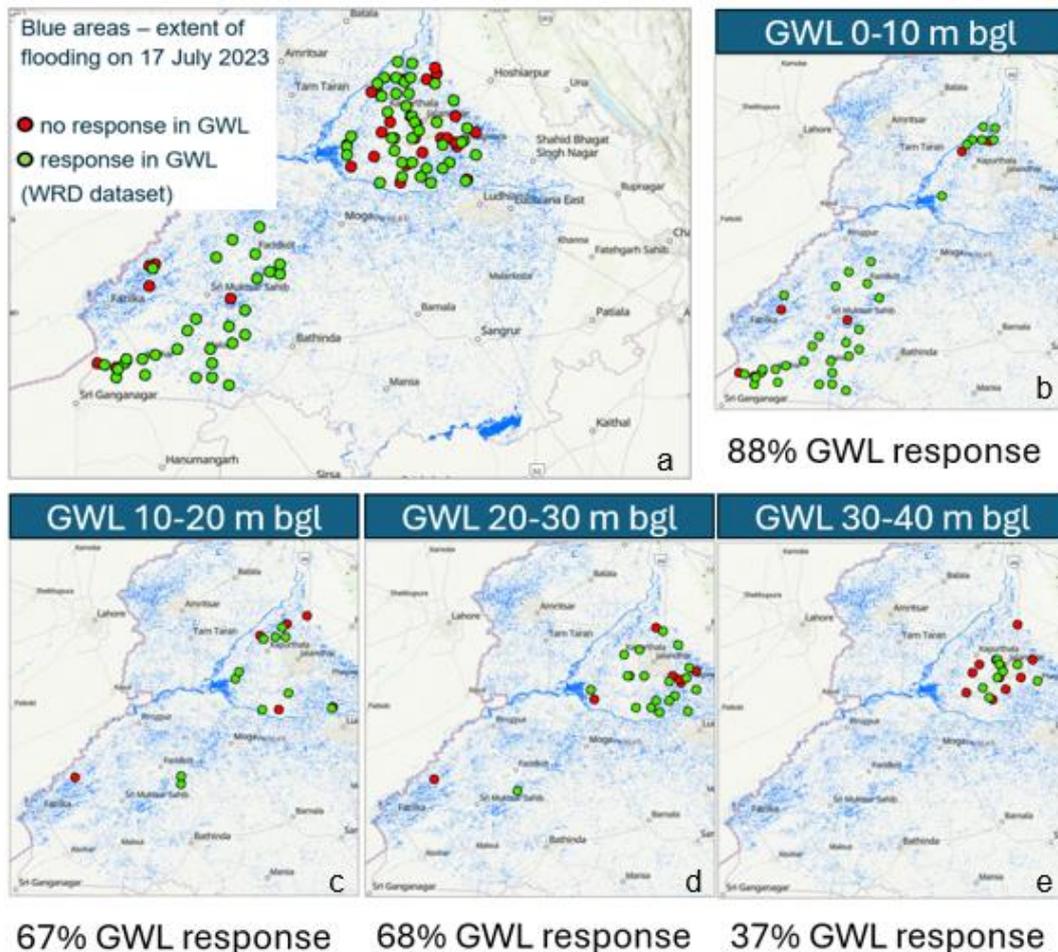


Figure 14 Observed groundwater level (GWL) response in mbgl to 2023 flooding events in the Bist-Doab and Malwa regions based on the WRD dataset. BGS © UKRI 2026. Made with Natural Earth free vector and raster map data © naturalearthdata.com. © IIT Mandi 2026.

Based on the visual classification of the WRD time series, four distinct response typologies were identified for sites that showed a groundwater level response during the flooding events (Figure 15a). The most common response pattern, seen in 36% of responsive sites, featured a higher first peak in July followed by a secondary, smaller rise in groundwater level in August. A quarter of responsive sites (25%) showed two peaks of similar magnitude. A unimodal peak during or shortly after the flood was observed at 21% of sites and a smaller group (18%) exhibited a more pronounced second peak.

An example of one of the 31% sites in the full dataset (including both responsive and non-responsive sites) that showed no discernible response to the 2023 floods is also provided in the same figure. The non-responsiveness of these sites may reflect either greater depth to groundwater, limited hydraulic connectivity to surface waters, or delayed recharge dynamics.

A larger groundwater response to rainfall in July than in August was observed in a slightly larger proportion of responsive sites in the Bist-Doab compared to the Malwa region (35% and 25%, respectively; dark-blue labels in Figure 14b). These sites in the Bist-Doab appear to correlate with local rainfall anomalies in Punjab in July (Figure 6; Figure 15b). A larger second peak was only observed in 9% of the responsive sites in Bist-Doab, but in 25% of the responsive sites in the Malwa region (Figure 15b). This higher peak groundwater level in response to the second floods (August) appears to correlate with the areas of river flooding that took place after water releases at Pong Dam (Section 4.1.3).

As illustrated by several examples in Figure 15a, the overall groundwater level behaviour appeared unaffected by the two flooding events, regardless of the specific response patterns observed. The predominant recessive (falling) trend in groundwater levels during the summer

was only briefly interrupted, before continuing until around October, which typically marks the onset of the groundwater recharge season.

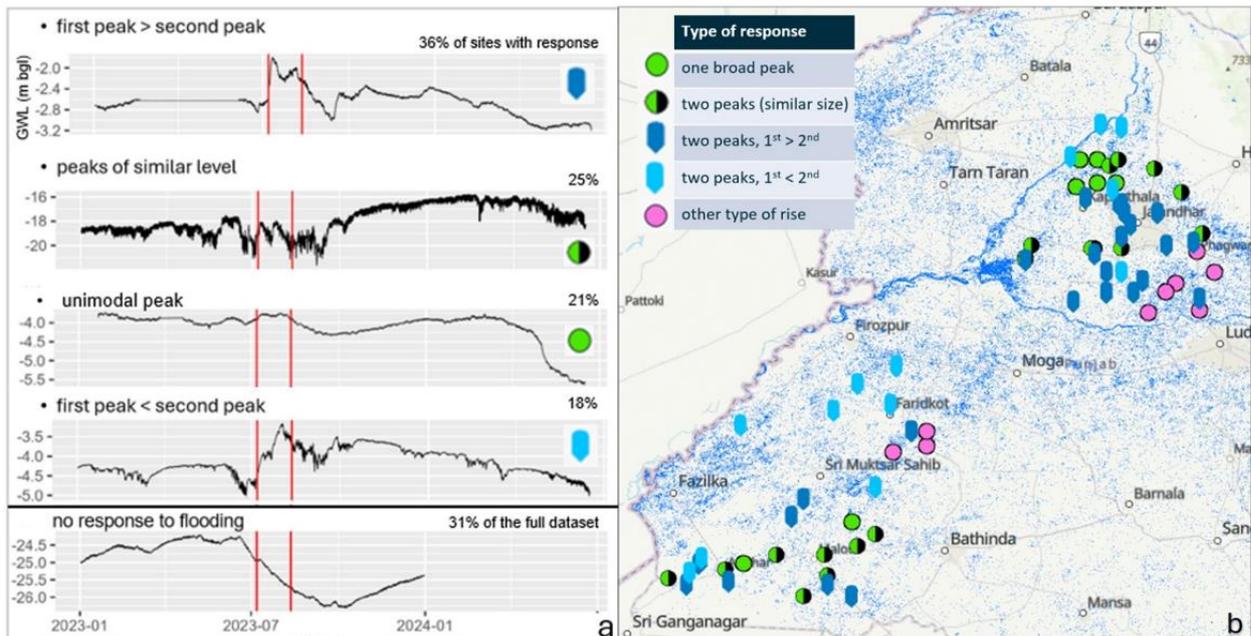


Figure 15 a Example of the different groundwater level responses observed in the WRD-dataset; coloured symbols indicate site locations on the map in Figure 15b where these responses were observed. b Spatial distribution of the different groundwater level responses by locations. ‘Other type of rise’ was used as category that could not be unambiguously classified. BGS © UKRI 2026. Made with Natural Earth free vector and raster map data © naturalearthdata.com. © IIT Mandi 2026.

Further contextualisation with lower-resolution groundwater level time-series data from the CGWB in Malwa was undertaken to investigate if the 2023 floods had a significant impact on groundwater level trends in the region. Out of the 64 sites that had been measured pre- and post-flooding in 2023 and had sufficient data to identify longer behaviour, a majority of 45% had relatively stable groundwater level behaviour over time, 28% showed a declining trend, and 8% a rising trend. The remaining data did not show a clear trend.

Groundwater level depth in this dataset ranged from few metres to about 20 mbgl. A limited number of measurements (one to a maximum of five per time series) were available after July 2023 for each time series, which limits the strength of the analysis but, based on visual inspection, trends did not seem to be broken by recharge occurring during or after the 2023 flooding events. This means that the impact of the flooding did not change overall recharge trends even in those areas with rapid groundwater level responses to the flooding events. However, although groundwater levels continued to recede following the flooding events, the recharge associated with those events may have prevented levels from falling as low as they typically would in other years. In other words, while the downward trend persisted, the temporary input of floodwater likely buffered the decline, resulting in relatively higher groundwater levels during the late dry season.

4.2.2 Natural and environmental tracers

Stable water isotopes ($\delta^{18}\text{O}$ and δD) were collected to increase understanding of recharge sources. Additional, tracers for groundwater dating (CFCs; SF_6 ; ^3H) were collected and analysed for a subset of groundwater sampling points in Punjab. These tracers do not pose a risk to human health at the concentrations detected in groundwater, but they do provide valuable insights into groundwater recharge processes.

4.2.2.1 STABLE ISOTOPES

Surface-water samples collected in HP by IIT Mandi indicate $\delta^{18}\text{O}$ values ranged from -11.49 to -4.95‰ with an average value of -8.12‰; δD values ranged from -75.24 to -26.26‰ with an average value of -49.18‰ (Figure 16).

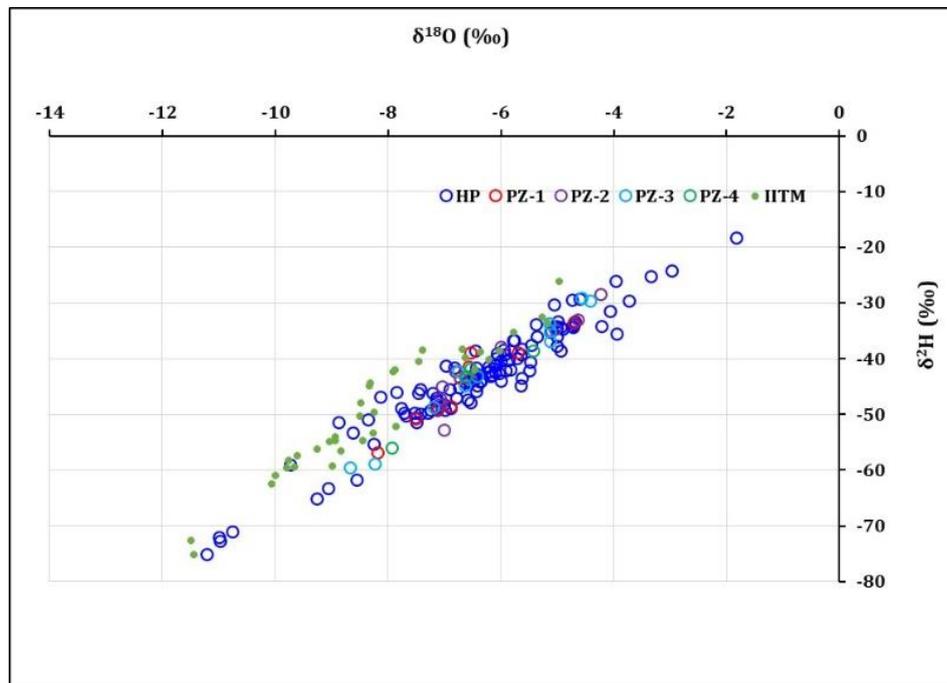


Figure 16 Plot between isotope values $\delta^{18}\text{O}$ and δD of the samples collected from Punjab and HP. © National Institute of Hydrology.

Groundwater $\delta^{18}\text{O}$ values in Punjab ranged from -11.20 to -1.82‰ with an average value of -6.36‰; δD values ranged from -75.21 to -8.35‰ with an average value of -43.13‰. The values of $\delta^{18}\text{O}$ and δD show the wide variations in the groundwater values, mirroring the variation in current rainfall and recharge from the river and canals. Higher depletion of $\delta^{18}\text{O}$ may be due to the processes involved before the water reaches the aquifer and recharge from a combination of different sources including precipitation and surface waters. The isotope characterisation is shown in Table 2.

Table 2 Isotope characterisation of water samples in Punjab (Krishan et al., 2021).

| Source | Equation* | Range $\delta^{18}\text{O}$ | Range δD |
|---|--|-----------------------------|------------------------|
| GMWL (Rozanski et al., 1993) | $\delta\text{D} = 8.17\delta^{18}\text{O} + 10.35$ | N/A | N/A |
| Precipitation (Bhaddi) | $\delta\text{D} = 6.8 \times \delta^{18}\text{O} - 2.77$; $R^2 = 0.96$; $n=286$ | 9.2, -16.6 | 72.2, -128.5 |
| | $\delta\text{D} = 7.9 \times \delta^{18}\text{O} + 5.48$; $R^2 = 0.96$; $n=322$ | 10.9, -15 | 67.5, -117.3 |
| Precipitation (Dolbaha) | $\delta\text{D} = 7.9 \times \delta^{18}\text{O} + 5.56$; $R^2 = 0.98$ | 5.8, -14.8 | 51.5, -116.3 |
| Precipitation (Chandigarh; Patiala; Sirsa) (Joshi et al., 2018) | $\delta\text{D} = 7.15 \times \delta^{18}\text{O} + 2.60$; $R^2 = 0.98$ | N/A | N/A |
| Precipitation (Delhi) (Pang et al., 2004) | $\delta\text{D} = 5.6 \times \delta^{18}\text{O} - 5.26$; $R^2 = 0.80$; $n= 167$ | -4.97, -10.1 | -33.2, -66.8 |
| River Beas | $\delta\text{D} = 7.1 \times \delta^{18}\text{O} - 0.40$; $R^2 = 0.96$; $n= 51$ | 0.15, -12.6 | -18.6, -90.7 |
| River Sutlej | $\delta\text{D} = 6.8 \times \delta^{18}\text{O} + 0.38$; $R^2 = 0.97$ | -6.06, -10.9 | -42.7, -74.5 |
| Canal | $\delta\text{D} = 6.1 \times \delta^{18}\text{O} - 6.2$; $R^2 = 0.95$; $n= 325$ | 2.39, -10.9 | 12.5, -74.8 |
| Groundwater (< 60 m) | $\delta\text{D} = 5.9 \times \delta^{18}\text{O} - 7.9$; $R^2 = 0.91$; $n= 175$ | -0.71, -11.3 | -13.5, -76.9 |
| Groundwater (60 to 150 m) | $\delta\text{D} = 6.3 \times \delta^{18}\text{O} - 4.1$; $R^2 = 0.89$; $n= 29$ | -5.6, -9.4 | -34.4, -64.4 |
| Groundwater (150 to 250 m) | $\delta\text{D} = 7.4 \times \delta^{18}\text{O} + 3.9$; $R^2 = 0.93$; $n= 13$ | -4.5, -8.2 | -26.9, -53.6 |
| Groundwater (>250 m) | $\delta\text{D} = 8.17\delta^{18}\text{O} + 10.35$ | N/A | N/A |

*(calculated from monthly weighted average)

In south-west Punjab, the isotope results from 36 groundwater samples obtained during 2022 and 2024 were compared. Isotope values of groundwater in 2024 are closer to values expected of rainfall when compared to the groundwater samples from 2022, for both shallow and deep aquifers (Figure 17 and Figure 18).

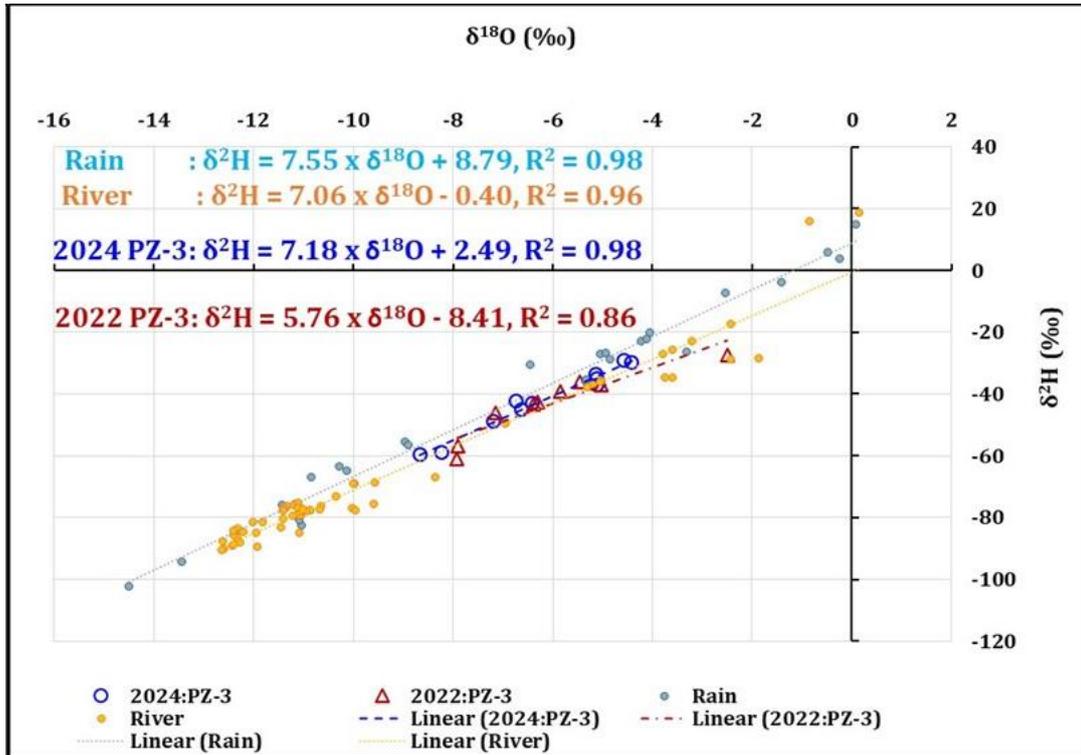


Figure 17 Plot between isotope values $\delta^{18}\text{O}$ and δD of the groundwater samples collected from shallow aquifers during years 2022 and 2024. © National Institute of Hydrology.

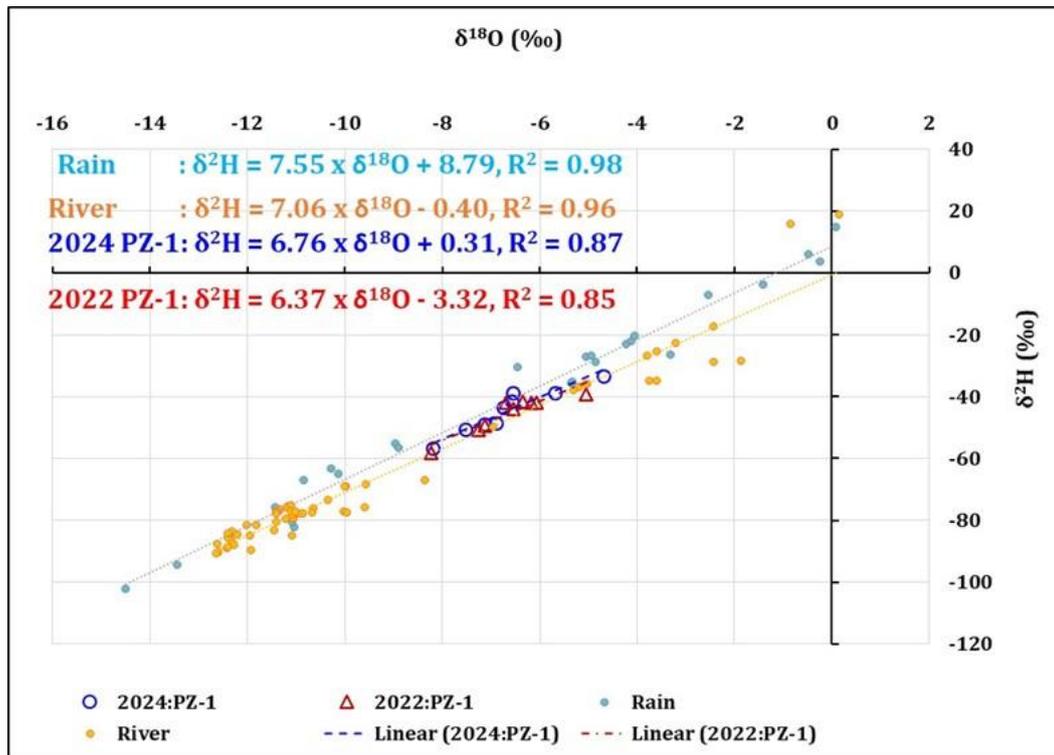
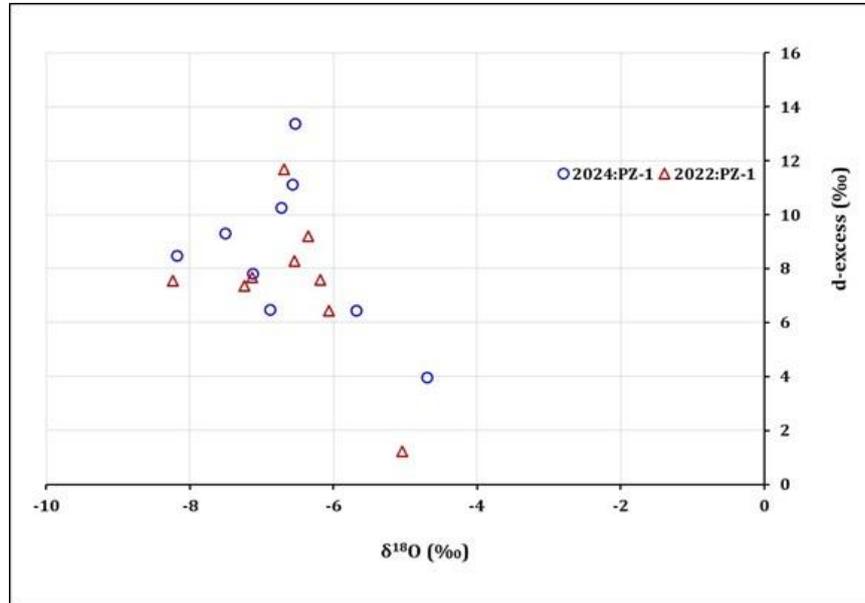


Figure 18 Plot between isotope values $\delta^{18}\text{O}$ and δD of the groundwater samples collected from deep (bottom) aquifers during years 2022 and 2024. © National Institute of Hydrology.

To understand the original source of water (recharge source in case of groundwater), D-excess of individual samples were estimated using the equation $d = D - 8 \times \delta^{18}O$. Figure 19 indicates a low to medium correlation between D-excess and $\delta^{18}O$ values, which suggests that evaporation shifted the enriched $\delta^{18}O$ and reduced D-excess values in 2024. This may suggest the possibility of increased mixing of surface water with groundwater in the 2023 flooding event.

(a)



(b)

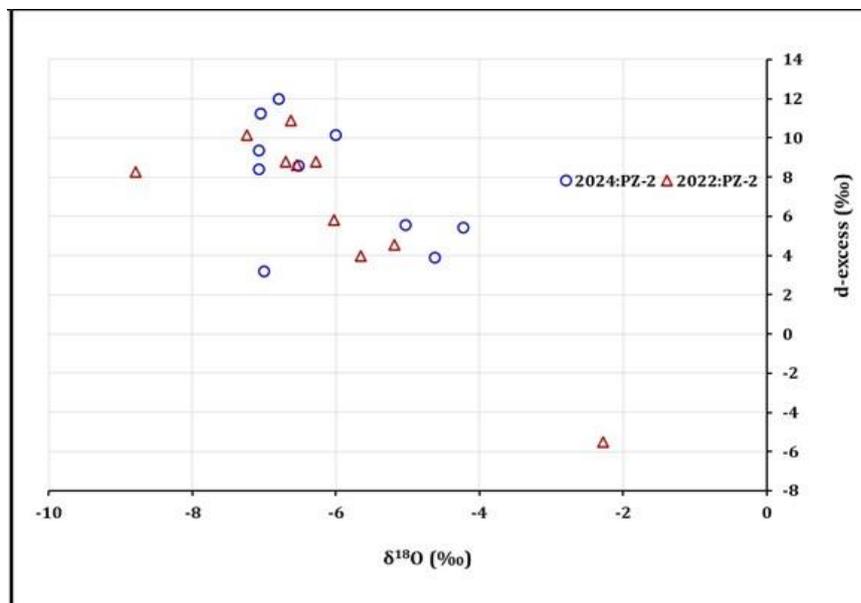


Figure 19 Plot between isotope values $\delta^{18}O$ and D-excess of the groundwater samples collected from shallow and deep aquifers during years (a) 2022 and (b) 2024. © National Institute of Hydrology.

4.2.2.2 RESIDENCE TIME OF TRACER (SF_6 ; CFCs; ^3H)*CFCs and SF_6*

SF_6 and CFC-12 data for those samples with data from 2022 and 2024 are shown in the bow-plot in Figure 20. Different lines refer to different models with which the average recharge year of the groundwater can be calculated. The best fit for most of the samples is achieved with the piston flow model (PFM), which assumes a uniform vertical recharge, that is, recharge water moves downward through the soil and unsaturated zone like a 'piston': newer water pushes older water downward, without mixing. However, some of the data points also correlate with an exponential mixing model (EMM) and binary mixing model (BMM). EMMs and BMMs are more often applicable where mixing of water or surface water/groundwater occurs and could, in some instances, also be indicative of flooding impacts.

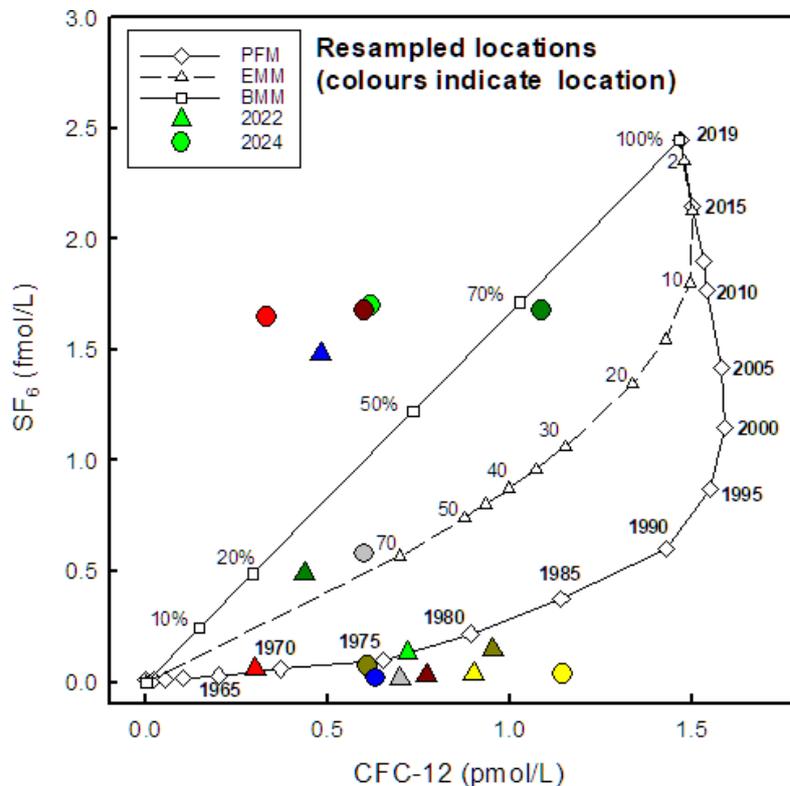


Figure 20 Bow-plot of SF_6 vs. CFC-12 concentrations for those sites sampled in both 2022 (circles) and 2024 (triangles). The filled colours represent individual sites, allowing comparisons of the results collected in 2022 and 2024. Different lines refer to different models with which the average recharge year of the groundwater can be calculated. The best fit is achieved with PFM, which assumes of uniform vertical recharge. BGS © UKRI 2026.

Figure 20 also shows that SF_6 and CFC measurements are broadly in good correspondence, but there are some outliers in the SF_6 measurements, which have an over-modern fraction of SF_6 . An over-modern fraction of SF_6 in groundwater refers to a situation where the concentration of SF_6 in a groundwater sample is higher than what would be expected from equilibrium with the modern atmosphere. There is limited evidence that natural geochemical processes could have caused the elevated SF_6 measurements. A more likely explanation is that excess air could have been trapped during heavy recharge (such as the flooding events). SF_6 is very sensitive to excess air, much more so than CFCs, and this could have caused the measured concentrations to rise.

Since the contamination of a subset of samples with SF₆ would affect the estimation of the mean groundwater age, the remainder of this section is focused on the CFC-12 analysis. Based on CFC-12 measurements, average groundwater ages differed only slightly at 26 boreholes locations sampled in 2022 and 2024, with medians of 1976 and 1974, respectively (Figure 21, left). In addition to the borehole samples, 25 CFC samples were also obtained from handpumps in Punjab. Analysis results for the handpumps did not differ substantially to those from the boreholes with similar average recharge year (median 1974) as the boreholes.

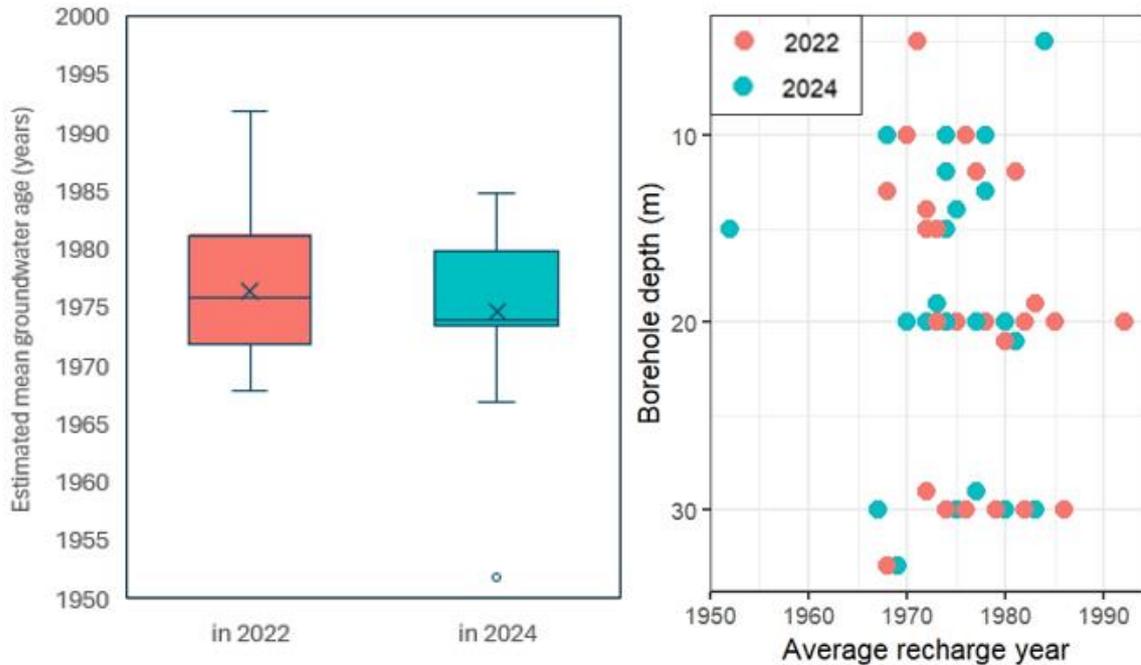


Figure 21 Estimated average groundwater age of 26 resampled boreholes in 2022 and 2024 based on CFC-12 measurements as box-plot (left) and shown by borehole depth and sampling year (right). BGS © UKRI 2026.

There was little variation and no clear trend of average groundwater ages in relation to borehole depth (Figure 21, right). This indicates that there has not been a major shift in the groundwater age profile due to the flooding. This is perhaps not surprising as the annual precipitation (and hence likely recharge) was not significantly different to the long-term average and, considering that the interpreted ages are mean residence time, one would not expect a major shift unless a very significant proportion of new recharge water had recharged during the flooding.

³H

The results for ³H analysis are shown in Figure 22. ³H values range between 1.3 to 33.6 TU with average values of 8.3 TU. These values clearly show modern recharge in most of the shallow piezometers with high values (over 10 TU).

Low ³H values were observed in the Bist-Doab, suggesting recharge more than 30 to 40 years ago. Low ³H was detected in samples from the deeper aquifer, indicating a recharge age of over 50 years. Modern recharge in most of the shallow groundwater and older recharge in the intermediate and deeper aquifers likely indicates, in agreement with the groundwater level analysis, flood impacts on the shallow groundwater. Thus, ³H results appear to provide support for recent water ingress, possibly derived from the flooding that occurred in 2023.

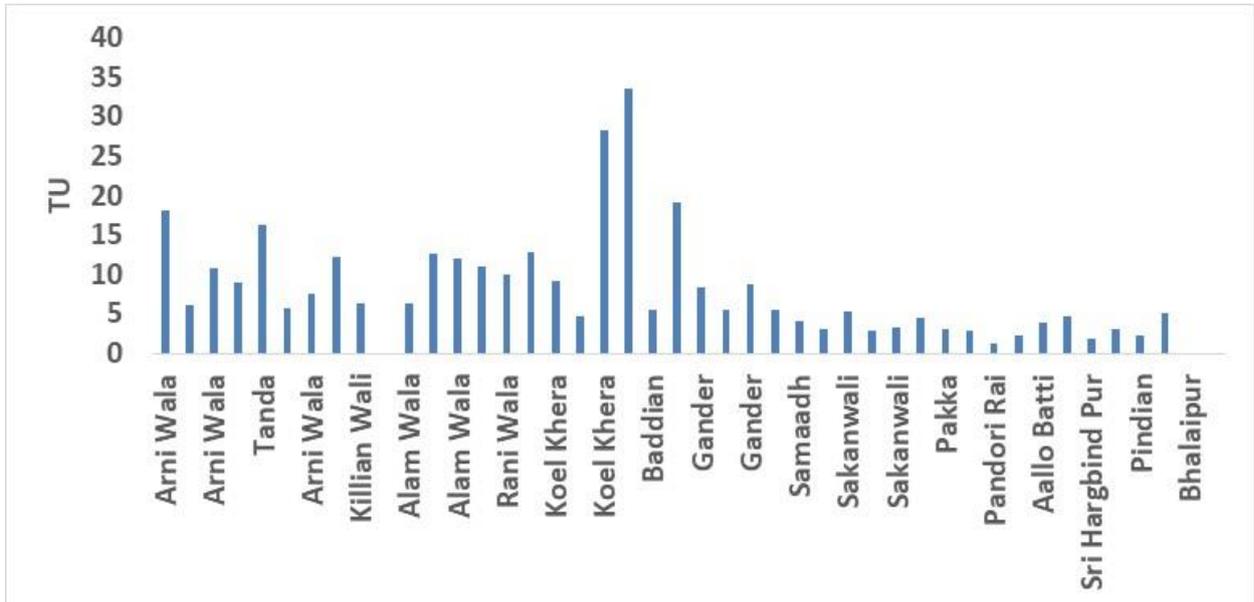


Figure 22 ³H values of groundwater samples from Punjab. © National Institute of Hydrology.

4.3 ASSESSING GROUNDWATER QUALITY IMPACTS

4.3.1 Water chemistry samples

The major ion chemistry of both surface and groundwater samples collected in 2024 was dominated by calcium, bicarbonate and chloride, although compositional differences were apparent between sample types and regions (Figure 23). River water samples from HP displayed more dilute chemistries overall, with clustering towards calcium/bicarbonate. There was little variation in surface water composition by sampling round (Figure 23, left). By contrast, groundwater samples — particularly those from the Malwa region — displayed a wider compositional range, with numerous samples plotting towards the calcium/chloride and sodium/chloride facies (Figure 23, right).

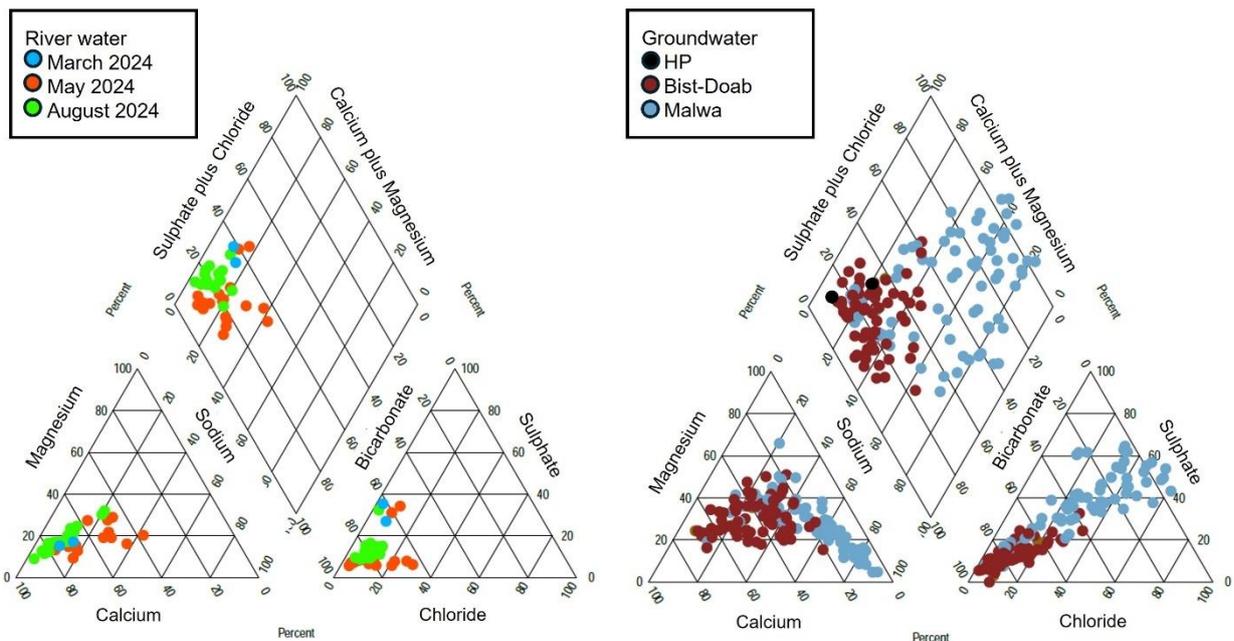


Figure 23 Triangular Piper plot of river water samples collected in HP by time of sampling (left) and for groundwater samples by region (right). All groundwater samples were collected in 2024. BGS © UKRI 2026.

Trace element analysis further revealed that a significant proportion of samples exceeded World Health Organization (WHO) drinking water standards. While 52% of samples analysed for fluoride and nitrate exceeded guideline thresholds, exceedances of minor and trace elements were even more prevalent, affecting approximately 63% of the samples (Table 3). Groundwater in the Malwa region was particularly affected, with frequent exceedances for arsenic, manganese and uranium. These findings align with previous work identifying the Malwa region as a hotspot for groundwater quality degradation linked to both geogenic sources and intensive agricultural land use (Lapworth and el., 2017). In contrast, surface water in HP showed relatively few exceedances, consistent with the more dilute chemistry observed in the upper catchment.

Table 3 WHO drinking water thresholds exceedence in HP and Punjab. Exceedance of drinking water limit (DWL) based on WHO threshold from 2022 (WHO, 2022) of F > 1.5 mg/L, NO₃ > 50 mg/L, As > 10 µg/L, B > 2400 µg/L, Mn > 80 µg/L, Pb > 10 µg/L and U > 30 µg/L.

| Sample type & region | Analysed samples (n) | Count (n) of DWL exceedance | | Analysed samples (n) | Count (n) of DWL exceedance | | | | |
|----------------------|-------------------------|-----------------------------|-----------------|-------------------------|-----------------------------|----------|-----------|----------|-----------|
| | | F | NO ₃ | | As | B | Mn | Pb | U |
| Surface water | 37 | 2 | 0 | 5 | 0 | 0 | 0 | 0 | 0 |
| HP | 37 | 2 | 0 | 5 | 0 | 0 | 0 | 0 | 0 |
| Groundwater | 149 | 61 | 40 | 47 | 2 | 9 | 11 | 4 | 23 |
| HP | 3 | 1 | 2 | 1 | 0 | 0 | 0 | 0 | 0 |
| Punjab, Bist-Doab | 71 | 31 | 14 | 13 | 2 | 0 | 8 | 0 | 0 |
| Punjab, Malwa | 74 | 29 | 24 | 33 | 0 | 9 | 3 | 4 | 23 |
| Total | 186 | 63 | 40 | 52 | 2 | 9 | 11 | 4 | 23 |

SEC values, which are field measurements that can be used as a proxy for salinity issues in waters, were measured in situ at all sampling locations. SEC values measured in waters from handpumps corresponded broadly to those measured in the shallow boreholes of the same area (Figure 24). There were strong regional differences, with SEC values in the Bist-Doab region averaging 887 µS/cm and more strongly ionised samples from the Malwa region, which averaged 2415 µS/cm. This is in accordance with previous studies, which identified especially the south-western part of the Malwa region as having stronger salinity issues than the north-eastern part of the Punjab, which is more drained by the Himalayan rivers (Romana et al., 2024).

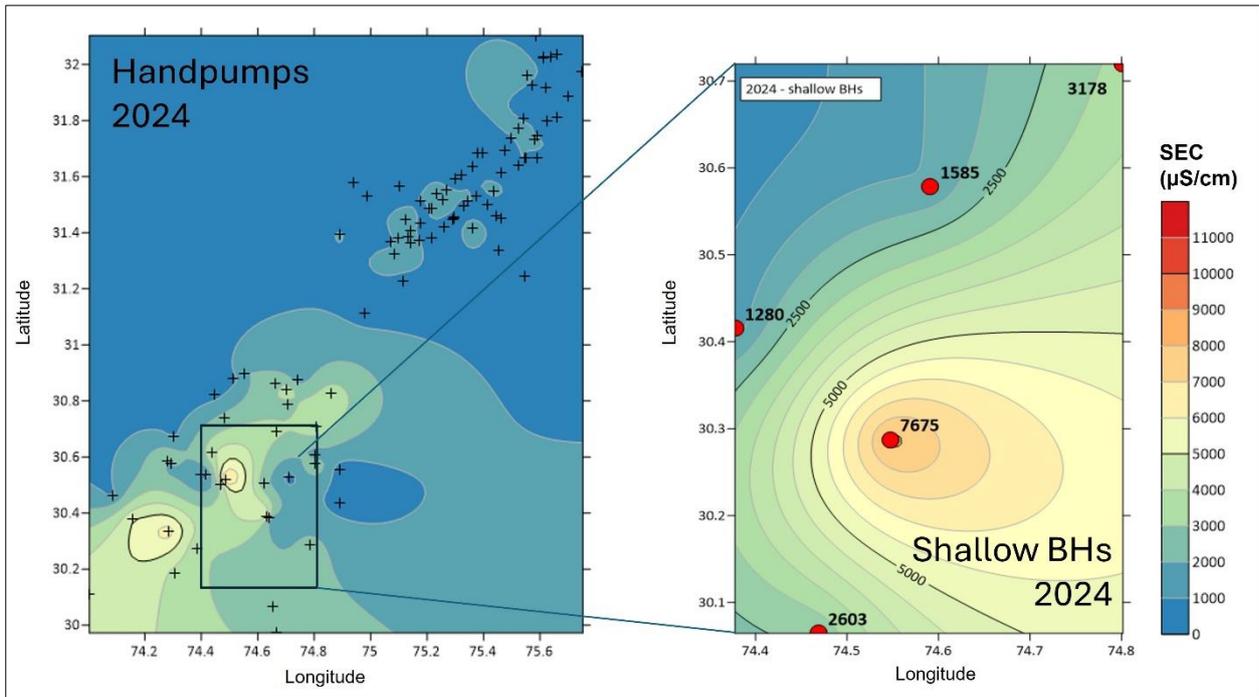


Figure 24 Sampling locations and interpolated map of SEC. The left panel shows handpump sampling locations (crosses) across the Malwa and Bist-Doab regions; the right panel presents shallow borehole sampling locations (red dots) in a zoomed-in area. Background colours represent interpolated SEC values, with the scale shown to the right. Measured SEC concentrations of the handpumps are provided in bold text next to each location. BGS © UKRI 2026.

When comparing SEC data from various borehole depths, the nested piezometers (boreholes) in the Malwa region had significantly ($p > 0.05$) higher values in the deeper boreholes compared to those that are shallow or medium in depth (less than 30 m; Figure 25 left), indicating an increase of SEC with depth, which can often be observed in deeper aquifers.

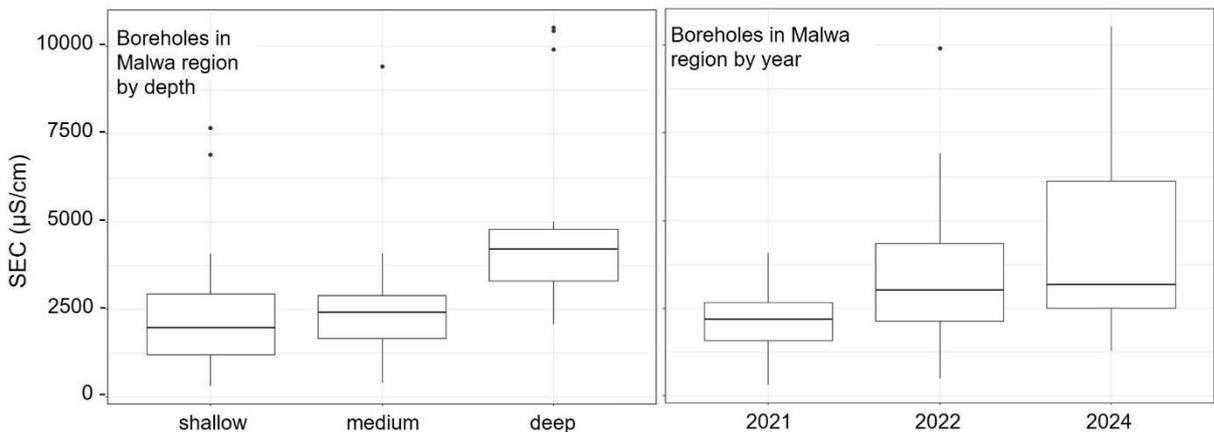


Figure 25 Measured SEC values in boreholes in the Malwa region by borehole depth (left) and by sampling year (right). Classification of borehole depths: shallow ≤ 15 m; medium 15 to 30 m; deep more than 30 m. BGS © UKRI 2026.

4.3.2 Comparison of water chemistry pre- and post-flooding 2023

A repeat analysis was available for 24 boreholes (distributed over nine locations in the Malwa region; Figure 2). There was no strong variation of major ion composition that could be observed between the two sampling rounds as shown in the Piper plot in Figure 26, though two of the samples showed an increase of chloride and sulfate in 2024, which can generally be indicative of flood water impacts.

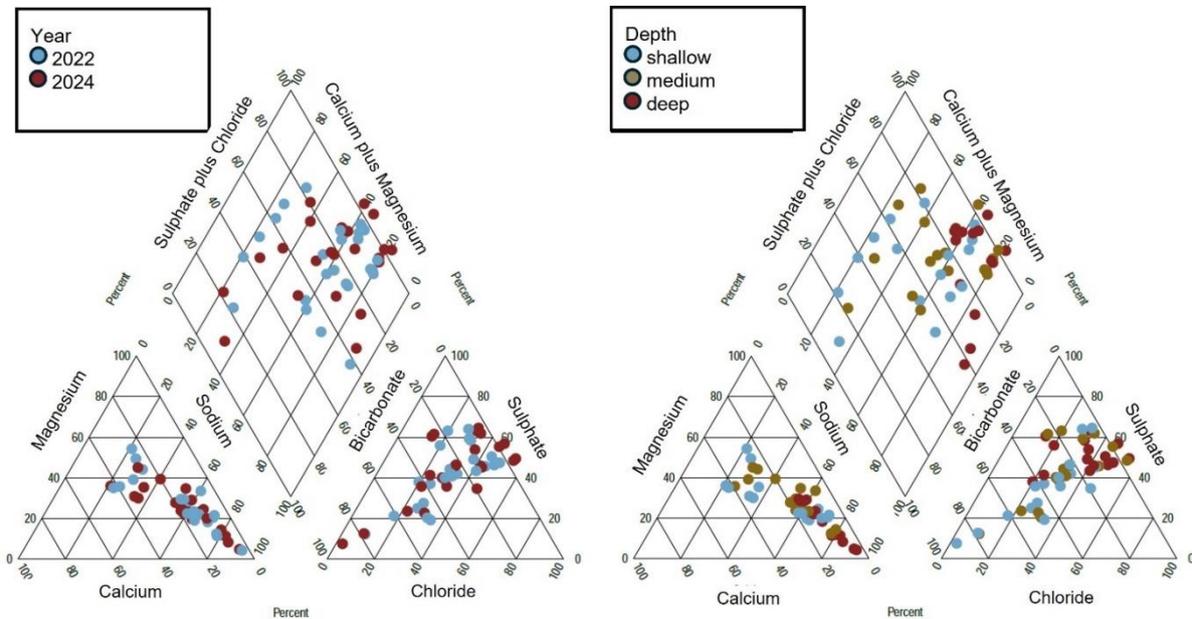


Figure 26 Samples from 24 boreholes from nine locations in the Malwa region (Punjab) by sampling year (left) and by borehole depth (right). BGS © UKRI 2026.

The major ion chemistry of the resampled locations in the Malwa region was dominated by sodium, sulfate and chloride, with 32% of samples being of Na-ClSO₄ type and 25% Na-SO₄. There was a strong trend with borehole depth of sodium being the dominating cation (making up over half of total anions per litre) in 56%, 69% and 100% of the samples from the shallow, medium and deep boreholes, respectively (Figure 26). Like the full dataset from 2024, the repeat samples showed exceedances for nitrate, boron, manganese, lead and uranium. There were no strong variations between the sampling years, though WHO threshold levels were exceeded slightly more often post-flooding (in 2024).

Table 4 Comparison of WHO drinking water thresholds exceedance by borehole depth pre-and post the 2023 flooding. Exceedance of drinking water limit (DWL) based on WHO threshold from 2022 (WHO 2022) of $\text{NO}_3 > 50\text{mg/L}$, $\text{B} > 2400 \mu\text{g/L}$, $\text{Mn} > 80 \mu\text{g/L}$, $\text{Pb} > 10 \mu\text{g/L}$, and $\text{U} > 30 \mu\text{g/L}$.

| Year & sample type | Count (n) of DWL exceedance | | | | | |
|--------------------|-----------------------------|---------------|-----------|----------|----------|-----------|
| | (n) | NO_3 | B | Mn | Pb | U |
| 2022 | 24 | 5 | 4 | 0 | 1 | 4 |
| GW-shallow | 8 | 3 | 2 | 0 | 0 | 2 |
| GW-medium | 8 | 1 | 1 | 0 | 0 | 1 |
| GW-deep | 8 | 1 | 1 | 0 | 1 | 1 |
| 2024 | 24 | 7 | 7 | 2 | 3 | 7 |
| GW-shallow | 8 | 2 | 3 | 1 | 0 | 3 |
| GW-medium | 8 | 1 | 2 | 0 | 1 | 2 |
| GW-deep | 8 | 4 | 2 | 1 | 2 | 2 |
| Total | 48 | 12 | 11 | 2 | 4 | 11 |

Repeat measurements were also available for SEC in the Malwa region. At five of the locations these were available for two years pre-flooding and 2024 (Figure 2). Each of the five locations had nested boreholes, so that data is available from shallow, medium and deep boreholes. Based on statistical analysis, SEC was significantly different between the years 2021 and 2024 ($p < 0.05$; Figure 25, right), but there was a non-significant increase between the other years. This suggests an increasing trend in SEC values but no stronger shift or break of trend between the most recent measurement pre-flooding (2022) and post-flooding (2024). The lack of change of the trend indicates that any impact of flooding on SEC caused by the extreme flooding events in 2023 does not seem to be long term.

4.3.3 Indicators of microbial contamination

Depth profiles for a range of fluorophores and FIs for the collected dataset are presented by study region and for HP by sampling round (Figure 27). All samples from the Bist-Doab were collected from handpumps, which are of unknown depth. Given that water levels in the region are likely to be relatively shallow, a consistent depth of about 8 mbgl was assumed for the handpumps for the purpose of plotting the data, as this seems a reasonable depths for shallow borings and helps to distinguish the sites from the 10 m-boreholes in the figure.

Surface-water samples from HP in May and June had moderate fulvic acid, humic acid and humidification index, as well as a moderate FI, which indicates somewhat balanced microbial and terrestrial DOM sources. In August, tyrosine and tryptophan were slightly lower and the humidification index was higher, suggesting more humified organic matter and likely higher terrestrial influence, such as runoff from agriculture.

The handpump samples from Bist-Doab had low values for both fulvic and humic acids, which might be indicative of relatively stable conditions despite the proximity of the sample locations to the Beas River.

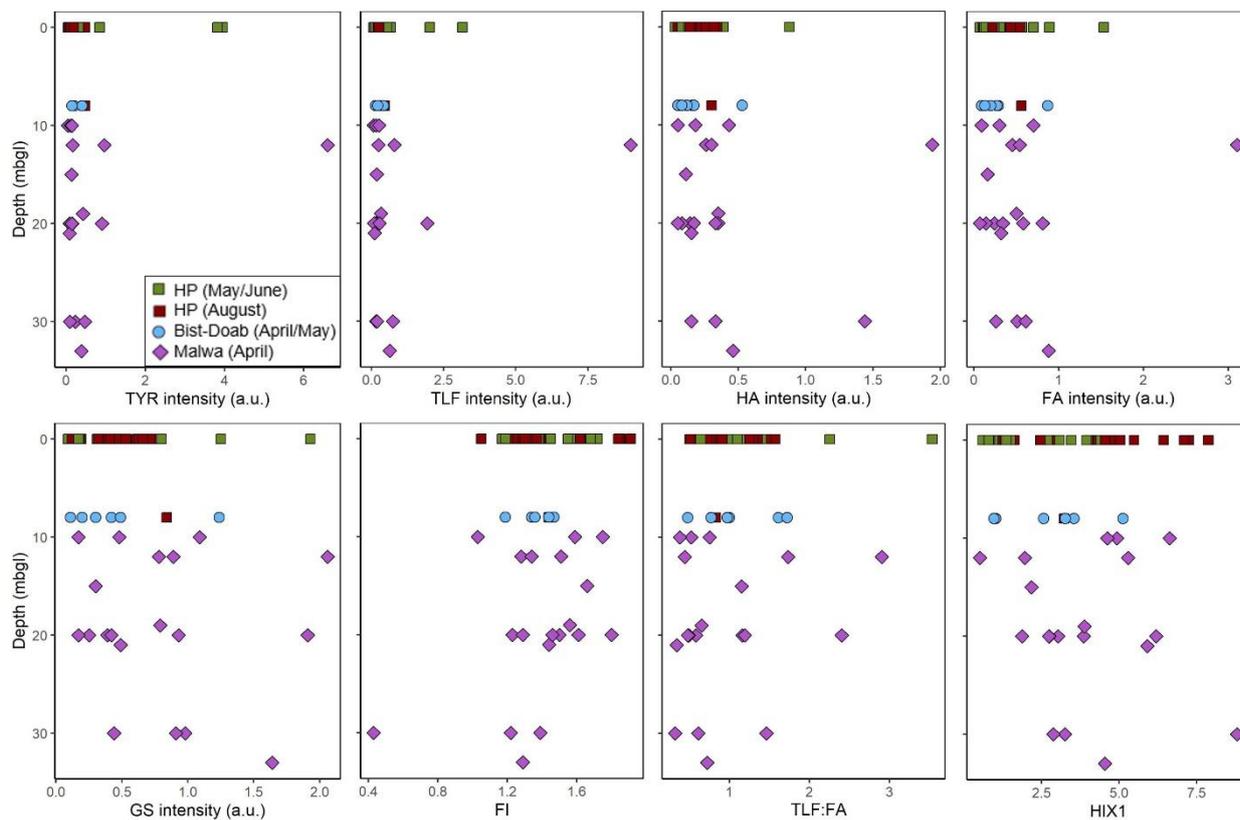


Figure 27 Depth profiles fluorophores and fluorescence indices. TYR: tyrosine; TLF: tryptophan (both protein-like); HA: humic acid; FA: fulvic acid; GS: gelbstoff; FI: fluorescence index; TLF:FA: tryptophan:fulvic acid ratio; HIX1: humidification index. BGS © UKRI 2026.

Borehole samples from the Malwa region fell broadly within the range of fluorophores and FIs that was observed in surface-water samples in HP, which could indicate some ingress of surface waters. There are no clear depth trends for any of the EEM indicators but some of the deeper boreholes (more than 30 mbgl) had lower average fluorescence and tryptophan:fulvic acid ratio and a higher average humidification index than the shallow boreholes. This suggests that some of the deeper boreholes are less affected by recent recharge or flooding. Average FI and TLF:FA were higher in the Malwa region than in the Bist-Doab, which is indicative of a higher impact from flood waters in this region.

In terms of health implication, none of the plotted values in Figure 27 has any direct regularity threshold under the WHO drinking water standards. However, elevated TLF intensities can be an indication of microbial contamination or the presence of organic matter from sewage or surface-water intrusion (Sorensen et al., 2018). Evidence from recent research has shown that fluorescence signals in groundwater may give an indication of the level of risk a borehole has for surface derived microbial contamination, for example from flood inundation, and that these signals are more persistent over time compared to faecal indicators, which are highly transient (Ward et al., 2021).

4.4 OUTREACH ACTIVITIES

4.4.1 Stakeholder engagement

The project actively engaged with key stakeholders from Punjab and HP throughout the project lifetime. Participants supported the project's aims and objectives and the research approach adopted. Participants expressed their thanks for the effort to involve and consult them regularly throughout the duration of the project and the efforts to disseminate the project findings. They also expressed their appreciation for what the project managed to achieve and for the efforts to

share the findings of the research. Headline feedback from those that attended project workshops included an increased recognition of the need for improved early warning and mitigation, and the value of the research in contributing to the evidence base required to develop such interventions.

Stakeholder engagement took place as follows:

- March 2024: project team attended FCDO workshop in Shimla, HP, and presented an overview of project aims and objectives. A total of 55 participants attended the workshop including farmers and policymakers, engineers, officers, hydrogeologists and scientists from:
 - Himachal Pradesh State Disaster Management Authority (HPSDMA)
 - IMD-Shimla
 - Department of Agriculture
 - Department of Horticulture
 - Jal Shakti Vibhag
 - Rural Development
 - HP State Pollution Control Board (HPSPCB)
 - non-governmental organisations (NGOs)
- April 2024: project team attended FCDO workshop in Chandigarh, Punjab and presented an overview of project aims and objectives. A total of 62 participants attended the workshop including farmers and engineers, officers, hydrogeologists and scientists from:
 - WRD
 - Department of Water Supply and Sanitation
 - IMD
 - Agriculture and Farmers' Welfare
 - Punjab state farmers and farm worker's commission
 - CGWB
 - NGOs
- July 2024: the project team organised an additional workshop in Punjab to present the aims and objectives to a more focused group of stakeholders, with online participation from Dr Donald John MacAllister and Dr Bentje Brauns of BGS. A total of 67 participants attended the workshop including policymakers, engineers, officers, hydrogeologists and scientists from:
 - WRD
 - Department of Water Supply and Sanitation
 - IMD
 - Agriculture and Farmers' Welfare
 - CGWB
 - Regional Pesticides Laboratory
 - NGOs
- A final workshop was held in March 2025 in Chandigarh, Punjab with online participation from Prof Alan MacDonald, Prof Dan Lapworth and Dr Donald John MacAllister of BGS, and representatives from FCDO. A total of 70 participants attended the workshop, including engineers, officers, hydrogeologists and scientists from:
 - WRD
 - Department of Water Supply and Sanitation
 - IMD
 - Agriculture and Farmers' Welfare
 - CGWB
 - Punjab Agricultural University (PAU)
 - Ludhiana city
 - NGOs

4.4.2 Additional capacity building events

Capacity building on the use of environmental tracer analysis was identified as a critical need during this project. The project therefore supported a training course for students, research scholars and academic laboratory staff from all over India between 24 and 26 July 2024, on environmental tracers in water resources management. A total of 230 registrations were received: 47 participants from a wide array of institutes were selected for the training course, with 30 participants attending the training.

The course consisted of 12 lectures, including two online lectures by BGS staff and two hands-on sessions on the use of instruments and data interpretation. The training lectures were provided by the subject experts of NIH Roorkee and BGS. The course included practical training on the use of the environmental tracers; the theoretical and practical sessions were designed in 75:25 ratio for better understanding of the use of environmental tracers by the participants.

Feedback was collected via a Google Forms survey sent to the participants. The participants appreciated the effective management and organisation of the training and agreed that the course content delivered the training objectives effectively, and that the course provided opportunities for practising and reinforcing what was taught.

Another training course, building on the material that was developed for the course delivered in 2024, was conducted in June/July 2025. The training was delivered by the NIH, Roorkee scientists with the expert lectures from BGS, UK.

4.4.3 Additional dissemination activities

Several additional dissemination activities took place throughout the course of the project:

- presentation of the flood inundation mapping results (Raaj et al., 2024) and the role of rain-on-snow events in flood intensification during the July 2023 HP floods (Bilal et al., 2024) at the Fall Meeting of the American Geophysical Union in Washington D.C., USA, in December 2024
- two presentations on the hydrometeorological analysis of the July and August 2023 floods and groundwater impacts, respectively, at the International Groundwater Conference (IGWC) in Roorkee, India, in March 2025
- a manuscript on the flood has been published in *Science of the Total Environment*.

5 Key findings and reflections

5.1 FLOOD CHARACTERISATION

Precipitation analysis identified two intense rainfall spells: 9 to 11 July and 14 August 2023. These events exhibited significant departures from climatological norms. The July spell preconditioned the study area, while the August event triggered severe downstream flooding.

A resurgence of heavy rainfall events (R50 mm; R100 mm) and short-duration extremes (R×1 day, R×5 day) has been observed during 2020 to 2023, particularly in the Beas Basin region of HP and Punjab, and comparable to the 1980s.

The model setup allowed for comparative analysis of dam and unmanaged-dam scenarios to evaluate the impact of dam operations during the August 2023 flooding events. Analysis revealed that controlled reservoir releases notably reduced downstream flood impacts, protecting approximately 78.7% more individuals compared to unmanaged-dam conditions.

The analysis of Pong Dam operations during the August 2023 floods in Punjab reveals the dam's pivotal role in flood mitigation through regulated water release strategies. Additionally, the GA-based optimisation framework with a piecewise penalty function successfully demonstrated an adaptive strategy for optimising dam releases.

5.2 ASSESSING CUMULATIVE GROUNDWATER RECHARGE

High resolution (15 minute) groundwater level data for 116 locations in the Bist-Doab and Malwa regions of Punjab indicated that groundwater levels at 69% of the sites responded (showed an increase in groundwater level) to the two flooding events in July and August 2023. Flooding in July was primarily driven by precipitation that occurred in Punjab, while groundwater responses in August were primarily adjacent to the river, indicating direct recharge by river flood, including water released from the Pong Dam. Additional (lower resolution) groundwater level data obtained for the Malwa region indicated that the 2023 flooding events did not appear to have a longer-term impact on groundwater level trends, likely because total monsoon precipitation in 2023 did not deviate significantly from long-term monsoon trends.

Stable isotope analysis from groundwater samples in 2022 show higher D-excess values than in 2024, suggesting mixing of surface water and groundwater. Combined, isotopes and natural tracer data suggest a small contribution to recharge following the flooding in 2023:

- CFC-12 data showed median ages between 1976 and 1974 in 2022 and 2024, respectively
- SF₆ data collected in 2024 indicated high levels of contamination, which may suggest rapid groundwater recharge following the floods
- ³H analysis in Punjab clearly shows modern recharge in most of the shallow groundwater but older recharge in the intermediate and deeper aquifers

Long-term, high-frequency groundwater level measurements were most important for distinguishing flood-induced groundwater recharge. Thus, long-term, high-frequency groundwater monitoring should be prioritised to help understand recharge trends.

5.3 ASSESSING GROUNDWATER QUALITY IMPACTS

River-water samples from HP displayed relatively dilute ion chemistries overall, with clustering towards calcium bicarbonate. By contrast, groundwater samples, particularly those from the Malwa region, displayed a wider compositional range, with numerous samples plotting towards the calcium/chloride and sodium/chloride facies.

Groundwater in the Malwa region showed frequent exceedances for arsenic, manganese and uranium; surface-water in HP showed relatively few exceedances and there was no strong variation of major ions between 2022 and 2024. A better water quality baseline with several years (and ideally seasonal) data would be required to confirm impacts of flooding on groundwater quality.

There were strong regional differences with SEC values in groundwater in the Bist-Doab region, averaging 887 $\mu\text{S}/\text{cm}$, and the more strongly ionised samples from the Malwa region, which averaged 2415 $\mu\text{S}/\text{cm}$. Comparison between SEC values in 2021, 2022 and 2024 from five locations with nested boreholes in the Malwa region indicate a statistically significant difference between 2021 and 2024, but not between the other years, suggesting an increasing trend in SEC values but no significantly strong shift between the most recent measurement pre-flooding (2022) and post-flooding (2024).

Microbial indicators (fluorescence EEM analysis) of surface waters in HP show moderate-to-high humification and organic load, consistent with seasonal flooding or runoff. Shallow groundwater in Malwa and HP shows elevated humic and fulvic content and high humification index values, which are both signals for floodplain interaction or leaching after rainfall. Some of the deeper groundwater sites in Malwa are enriched in organic matter, which could reflect the site-specific conditions and may be linked to the recent flooding.

5.4 PROJECT CHALLENGES

Conducting the drone surveys within the original budget proved challenging, so instead we used high-resolution satellite imagery for this aspect. Drone surveys would likely have provided finer topographic detail, which in turn could have refined estimates of the spatial extent of flooding and inundation depths. However, the use of high-resolution satellite imagery remains consistent with global research practice, and the results produced are robust and comparable with similar studies.

Obtaining sufficient historical data as a baseline for water chemistry changes induced by the flooding also proved challenging. This was because some of the data did not exist (for example, pesticide and fluorescence data) and, in other cases, relevant data was not easily accessible (for example, inorganic chemistry data).

We were unable to collect as many samples as we would have liked for trace metal analysis. This was, in part, because sample analysis was originally intended to be done in India, but this proved not to be possible and these samples had to be shipped back to the UK, increasing analysis costs.

Import of analytical standards for pesticide analysis proved challenging and contributed to delays in starting pesticide analysis. It was very challenging to find laboratories capable of doing fungicide analysis in India: we had to develop our own protocol for sample preparation for the laboratory that we identified for analysis, which caused significant delays. Unfortunately, because of these challenges, the pesticide analysis has not produced results of sufficient quality to be included in the analysis and report.

6 Conclusion and recommendations

Following successive flood events in HP and Punjab in July and August 2023, we have investigated the flood mechanisms in the upland areas of HP and the impacts on groundwater in Punjab. The key hydrometeorological mechanisms leading to the flooding in HP in July were elevated soil moisture levels, coinciding with rain on snow and a significant precipitation anomaly (about 400% greater than average daily monsoon precipitation) on 9 July 2023. These conditions meant that elevated soil moisture remained an issue into August, which resulted in further flooding towards the middle of August. However, overall monsoonal precipitation totals did not deviate from the long-term mean, despite several intervening rainfall events that, although not heavy, maintained elevated soil moisture levels.

The July event was caused by abnormally high rainfall in HP and Punjab, but flooding in August was a combination of preceding conditions (high soil moisture maintained by persistent rainfall between July and August) and high rainfalls in HP, leading to substantial inflow into and necessary but well-controlled releases of water from the Pong Dam into Punjab. The role of the Pong Dam was significant in regulating the flow of water during the floods, which limited the flow into Punjab and avoided significant flooding impacts in the downstream areas. However, this also limited the potential for groundwater recharge from river flooding.

Raw groundwater level data were collected from the Punjab WRD and CGWB. We found that 69% of groundwater sites we investigated showed a small but clear response to both flooding events. Three distinct patterns of response were identified:

- approximately 36% of sites displayed a higher peak groundwater level in response to the first flood event in July: these sites tended to be clustered in northern and eastern areas of the study areas in Punjab and appear to correlate with local rainfall anomalies in Punjab, indicating a stronger influence of pluvial flooding
- approximately 18% of sites displayed a higher peak groundwater level in response to the second floods: these sites tended to cluster in the south and west of the study area and closer to the river, and appear to correlate with river flooding
- 21% of sites saw similar responses to both flood events

Initial analysis therefore suggests distinct groundwater responses to pluvial and river flooding, with potential implications for the role of dams in managing downstream groundwater resources. Long-term groundwater level trends appear not to have been influenced by the flooding events, raising the possibility that long-term changes in monsoon precipitation, which are predicted to be a result of climate change, might be more important for groundwater recharge in this region than short-term, extreme events. However, further monitoring would be required to investigate this hypothesis.

Isotope analysis supports the groundwater level data and suggests that new water entered the aquifer during the July and August 2023 floods, compared to typical monsoon conditions. Measurements of CFC-12 at some sites did not show clearly younger recharge ages, but some SF₆ and ³H results did support the idea of recent recharge, consistent with the isotope findings. In situ SEC measurements, which can be used as a proxy for groundwater salinity, showed an increasing trend (independent of the flooding event) over time at selected sites that had historic data from 2021 and 2022, and were re-measured in 2024.

The fact that SF₆ contamination occurred could indicate that some rapid recharge happened during the flooding. Fluorescence, major and trace elements highlight poor water quality, especially in the Malwa region, but with limited difference between a small subset of historical data from pre-flooding data in 2022 and the 2024. While it is possible that some of these contaminants, particularly nitrates, may have mobilised during flooding, a better baseline with several years (and ideally seasonal) data would be required to confirm this finding.

Based on the results of this study, the following recommendations are made to support future flood response planning, groundwater monitoring, and water quality management in HP and Punjab:

6.1 RELEVANCE OF PRECEDING CONDITIONS FOR DAM MANAGEMENT AND EARLY WARNING SYSTEMS.

Our hydrometric and modelling analysis clearly demonstrates the effect of the preceding conditions (increased soil moisture) for surface runoff and consequential flow into dam, which may cause dam releases. While the 2023 events are a good demonstration of a well-managed event, they also highlight the need for dam managers to receive early warnings on soil moisture conditions in addition to meteorological conditions.

6.2 THE USE OF FLOOD WATER AND OPTIMISED DAM MANAGEMENT TO ENHANCE GROUNDWATER RECHARGE

Our results highlight the important role of the dams in mitigating downstream flooding. It is possible that dams could be managed more effectively throughout the year to optimise different needs (for example, electricity generation vs. flood alleviation) including enhancing surface-water distribution for agricultural needs and even groundwater recharge.

6.3 ENHANCED GROUNDWATER MONITORING NETWORKS

Section 3.2 highlights how high-resolution groundwater level data can provide improved understanding of differences in the recharge behaviour of aquifers and enable better analysis of extreme events. An extension of high-resolution groundwater level monitoring to any sites of particular interest would be recommended.

6.4 DEVELOPING BASELINE WATER QUALITY DATA

A long-term, seasonally resolved water quality monitoring programme should be established in the Punjab region. This would allow for improved interpretation of future flood impacts on groundwater chemistry and provide a stronger baseline against which to assess change. Monitoring should include both major ions and trace contaminants, with a particular focus on nitrate, fluoride and heavy metals, including arsenic, uranium and manganese.

6.5 IMPROVED ANALYTICAL CAPACITY FOR EMERGING CONTAMINANTS

The challenges faced during the pesticide analysis highlight the importance of local analytical capacity. Investment in local laboratory capability, including standardisation of protocols and access to required reagents and instruments, would help avoid future delays and reduce dependency on overseas analysis. Future studies should consider including a broader suite of emerging contaminants such as fungicides and pharmaceuticals, which are increasingly recognised as a concern in agricultural regions.

6.6 SATELLITE AND MODEL-BASED FLOOD RECONSTRUCTIONS

The successful use of Sentinel and Landsat satellite imagery, combined with comparative model scenarios (for example, with and without dam influence), suggests these tools could be integrated into a standard framework for flood mapping and impact assessment. This is particularly valuable in areas where field access is constrained, or post-event surveys are delayed. Expansion of this approach into near-real-time analysis would also support disaster response efforts and early warning systems.

6.7 STAKEHOLDER ENGAGEMENT AND DATA SHARING

Ongoing engagement with local and regional stakeholders, including WRD, CGWB and academic institutions, will be critical for translating findings into policy and practice. Establishing more formalised data-sharing arrangements, particularly for real-time groundwater levels and

water quality indicators, would strengthen the ability of agencies to act on early signs of deterioration or recharge opportunity. Capacity building through joint workshops and training events could also support sustained improvements in monitoring and analysis.

Abbreviations and acronyms

| | |
|-----------------|---|
| ³ H | Tritium (radioactive isotope of hydrogen) |
| BB | Beas Basin |
| BBMB | Bhakra Beas Management Board |
| BGS | British Geological Survey |
| BMM | Binary mixing model |
| CARA | Climate Action for a Resilient Asia |
| CFC | Chlorofluorocarbons |
| CGWB | Central Groundwater Board |
| cumec | Cubic metre per second |
| DEM | Digital elevation model |
| DO | Dissolved oxygen |
| DOM | Dissolved organic matter |
| EEM | Emission excitation matrix |
| EMM | Exponential mixing model |
| FA | Fulvic (acid)-like |
| FCDO | Foreign, Commonwealth & Development Office |
| FI | Fluorescence index |
| GA | Genetic algorithm |
| GLDAS | Global Land Data Assimilation System (NASA) |
| HEC-RAS | Hydrologic Engineering Center River Analysis System |
| HP | Himachal Pradesh |
| ICP-MS | Inductively coupled plasma mass spectrometer |
| IIT | Indian Institute of Technology |
| IMD | India Meteorological Department |
| mbgl | Metres below ground level |
| NGO | Non-governmental organisation |
| NIH | National Institute of Hydrology |
| PFM | Piston flow model |
| RoG | Rain-on-grid |
| SAR | Synthetic aperture radar |
| SEC | Specific electrical conductivity |
| SF ₆ | Sulfur hexafluoride |
| TLF | Tryptophan-like fluorescence |
| TU | Tritium units |
| USGS | US Geological Survey |
| WRD | Water Resources Department (Punjab) |
| μS/cm | MicroSiemens per centimetre |

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