Technical Report

Next Generation Monitoring of Surface waTer fRom space (TRACE): Monitoring small waterbodies for integrated storage management

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Contents

Introduction

Global water scarcity is intensified by population growth, urbanization, and climate change impacts such as droughts and floods. In India, for instance, agriculture consumes over 80% of freshwater, yet per capita availability is projected to fall significantly by 2031. Effective management is hindered by a lack of data; India's first water bodies census revealed over 2.42 million water bodies, 97.1% of which are in rural areas (NWIC). The vast majority are small ponds and tanks that are difficult to monitor using traditional field surveys.

Reservoirs play a significant role in water resource management of intra- and inter-annual streamflow fluctuations to facilitate water supply (domestic, irrigation, and industrial), flood control, hydroelectric power generation, recreation, and other water uses (Gao et al., 2012). In many countries, agricultural production is rainfed, causing a highly vulnerable situation dependent on rainfall fluctuations. This vulnerability is exacerbated by the inability to predict and manage rainfall and runoff, impacting food security, which would worsen with climate change. In such situations, even smaller water storages play a significant role in safeguarding domestic supplies, supporting agriculture (crop and livestock), and agricultural and economic productivity during dry periods (McCartney & Smakhtin, 2010). In India, government-led initiatives and international projects have contributed towards the development of storage infrastructure of volume <1 Mm^3 (Bouma et al., 2011; Massuel et al., 2014).

Large reservoirs are monitored using complex systems providing all essential information related to their operations. However, there is little information available on water availability and influence of small reservoirs and waterbodies (Ogilvie et al., 2018) as they are rarely monitored in situ due to their quantity, size, and geographical distribution. Traditional hydrometric observation networks are costly and logistically challenging to implement for small storages, considering the time, equipment, and transport investments required (Liebe et al., 2005; Alsdorf et al., 2007).

In this context, remote sensing technologies emerge as a critical tool for monitoring small waterbodies. Remote sensing offers scalable, cost-effective, and repeatable means to estimate storage volumes and track temporal changes across vast and dispersed waterbodies without the need for extensive field deployment. By integrating satellite imagery and advanced hydrological modelling, remote sensing can overcome the limitations of traditional monitoring, providing comprehensive spatial and temporal data essential for effective water resource management. This approach facilitates better assessment of water availability, supports optimized allocation during dry periods, and enhances flood risk management, thereby addressing the data gaps that hinder sustainable management of small water storages.

TRACE

Next Generation Monitoring of Surface waTer fRom space (TRACE) is a web-based geospatial application designed to bridge the data gap in global water storage monitoring. While traditional methods focus on large dams, TRACE utilizes multi-satellite Earth Observation (EO) data to monitor the millions of smaller water bodies (tanks, ponds, and reservoirs) critical for local resilience. Leveraging Sentinel-1 Synthetic Aperture Radar (SAR) data to overcome cloud cover limitations, TRACE provides fortnightly assessments of water surface area and volume. The tool employs machine learning for land-water segregation and a distance-based bathymetric algorithm for volume estimation. It is developed with an objective to monitor surface water storage with surface area greater than 0.5 ha. At a regular interval using a standard and consistent approach which is based on freely available scalable tools. Effective water management is hindered by a lack of consistent data for small water storages. Optical satellite sensors (e.g., Landsat, Sentinel-2, MODIS) often fail to provide continuous data due to cloud cover, which averages 66% globally and impedes monitoring during the critical monsoon seasons. TRACE addresses this by utilizing Microwave SAR (Sentinel-1) data, which can penetrate cloud cover to acquire reliable information year-round. The tool is designed to serve diverse applications, including drought and flood management, irrigation planning, and urban water supply monitoring.

Methodology

Water Surface Area Extraction

The methodology for quantifying water resources began with the extraction of Water Surface Area (WSA) using Sentinel-1 C-band interferometric wide-swath (IW) data, which provides continuous monitoring of surface water extent. Figure 1 show complete methodology flow of surface area extraction. Sentinel-1 was available in Google Earth Engine (Donchyts et al., 2022) on with pre-processing employed the ESA SNAP software for crucial steps including Thermal noise removal, Radiometric calibration to produce backscatter intensity (σint), and Terrain correction using SRTM 30. Data available in Earth Engine is pre-processed. After ingestion, further processing involved applying a Lee-sigma filter and terrain orbital noise corrections using FABDEM to minimize the impact of shadows. A critical step involved filtering imagery captured during high wind speeds (over 12 km/h) to avoid wind roughening effects, although data for months averaging 8.39 km/h were ultimately included in the analysis.

To improve the separation of water from land features, indices were calculated from the co-polarized VV and cross-polarized VH bands. The selected indices—the Normalized Difference Polarized Ratio (NDPI) (Mitchard et al., 2012) and the Radar Vegetation Index (RVI) (Holtgrave et al., 2020; Nasirzadehdizaji et al., 2019), along with the gamma corrected VV and VH bands, were chosen based on statistical and visual observations confirming their high contrast between land and water. Aggregation of these bands resulted in mean monthly images, upon which unsupervised *k*-means clustering was applied to classify the image into 10 classes. Water classes were identified by leveraging the JRC monthly water recurrence dataset (1984–2021); pixels showing a recurrence greater than 70% were designated as water. Following classification, morphological processing (erosion followed by dilation) was applied to the water class layer to remove residual holes and stray pixels.

The maximum water surface area (WSA) boundary was determined through a time-series analysis spanning 2018–2022. Monthly water-land extent rasters were summed to create a variability layer, ranging from 0 (permanent land) to 12 (water presence year-round). This layer allowed for the exclusion of transient water features that might be misclassified as waterbodies, such as paddy fields, rivers, and canals, resulting in a filtered layer used to generate the final boundary polygon.

Bathymetry generation and Volume estimation

This maximum WSA boundary, along with maximum water depth (D_{max}), was essential for the subsequent phase of generating bathymetric information using the distance method (Khazaei et al., 2022). Depth (D) was estimated using the formula $D = (l \text{ X } D_{max})/L$, where l is the Euclidean distance to the shoreline and L is the maximum distance to the shoreline. D_{max} values were collected from authoritative national sources: India WRIS (NWIC) for larger reservoirs and Bhuvan WBIS (NRSC (ISRO)) for smaller waterbodies.

The final bathymetry layer was created by converting the derived depth values into a composite elevation-depth raster. This step involved merging the derived depth layer with the FABDEM elevation raster, specifically to correct for the masking and flattening of waterbodies common in standard Digital Elevation Models (DEMs). Water level and volume were then derived using a simplified approach requiring the composite DEM and the water surface area. Water level (h) was estimated by selecting the edge pixels of the WSA and extracting their elevation values from FABDEM; the mean of these extracted elevation values was used as the single water level for the entire waterbody to minimize uncertainties associated with the DEM. Volume (V) was calculated by summing the volumes of individual voxels across the water surface area to yield the volume in cubic meters, which was converted to billion cubic meters (BCM).

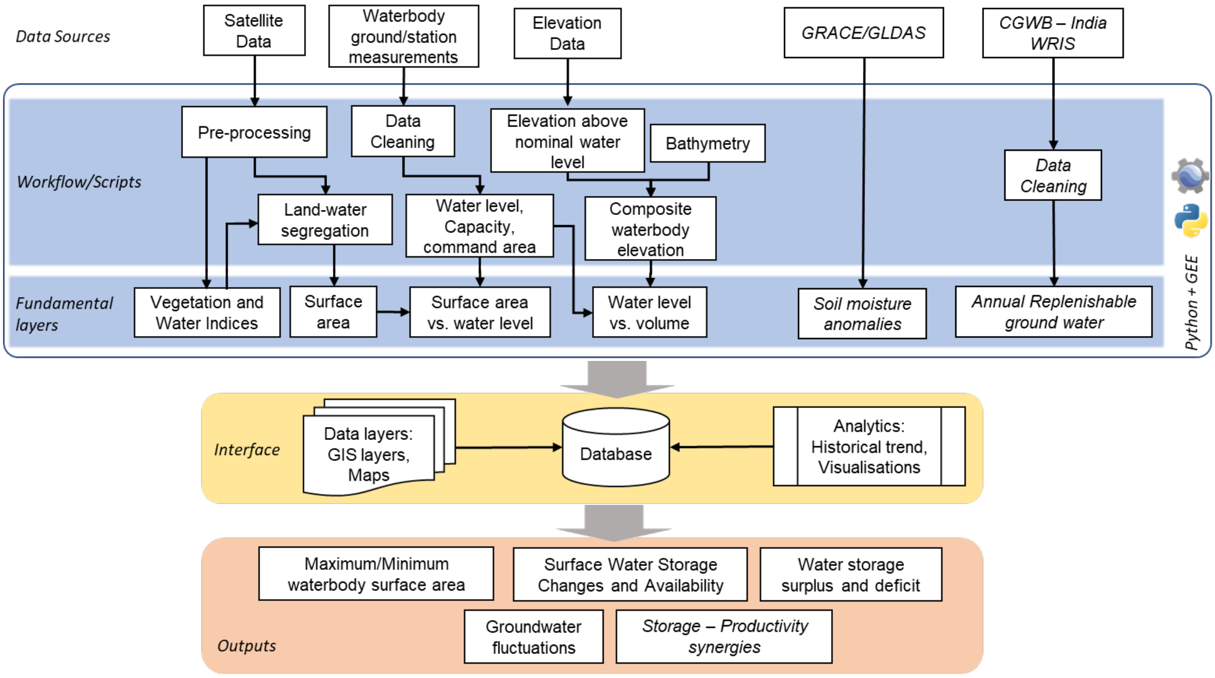


Figure 1: TRACE methodology framework for estimating Water surface area, water level and volume

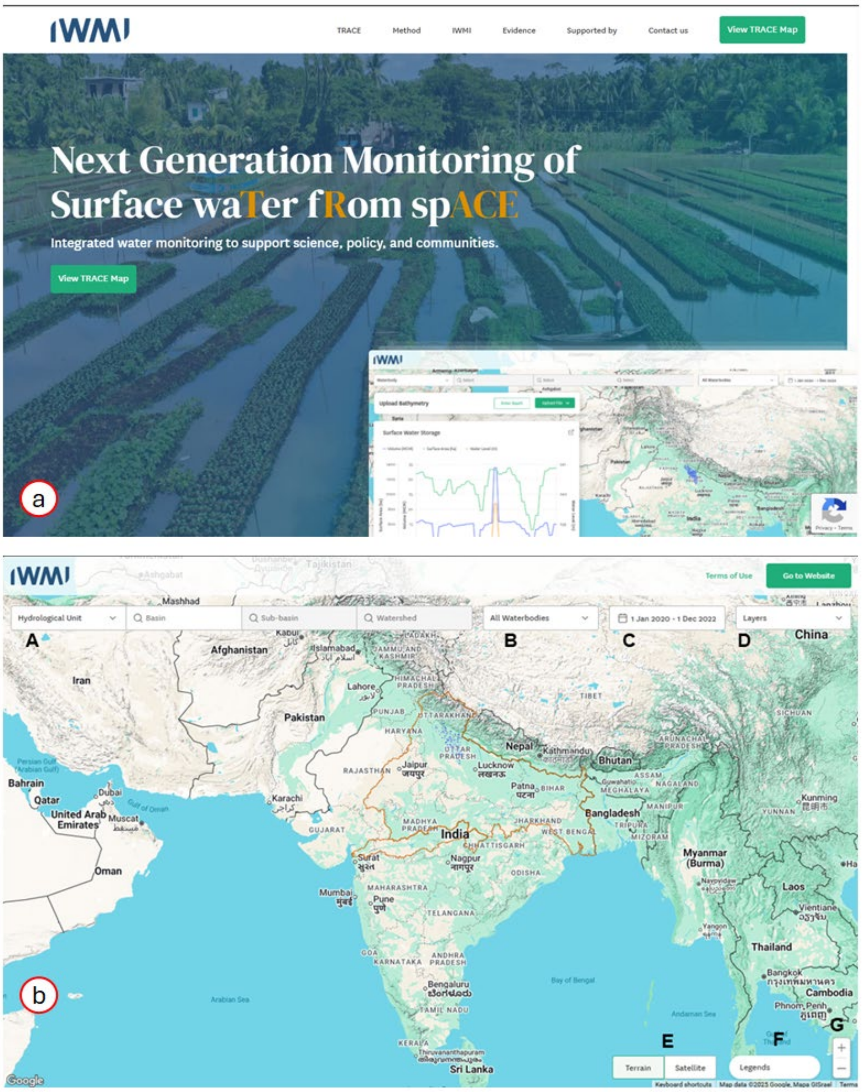
Groundwater and Terrestrial Water Storage

TRACE also includes data from other sources. The Central Ground Water Board (CGWB) provides data on annual replenishable groundwater resources, which is accessible through the India Water Resources Information System (India WRIS). This data represents the volume of groundwater that can be naturally recharged and sustainably utilized each year, accounting for rainfall, surface water inflows, and aquifer characteristics. The CGWB's annual replenishable water estimates are critical for water resource planning and management, particularly in regions where groundwater is a primary source for agriculture, domestic, and industrial uses. Access to this data via India WRIS enables comprehensive spatial analysis and supports informed decision-making for sustainable groundwater use and conservation across India. In addition to CGWB data, the Gravity Recovery and Climate Experiment (GRACE) satellite mission provides valuable insights into terrestrial water storage changes, including groundwater variations. GRACE measures temporal changes in Earth's gravity field, which reflect variations in total water storage encompassing surface water, soil moisture, groundwater, and snow. By isolating terrestrial water storage anomalies, GRACE data complements ground-based observations by offering large-scale, integrated assessments of groundwater depletion or recharge trends over time.

Using all these datasets in an integrated approach supports more informed water resource planning and management by addressing the complementary roles of surface and groundwater in meeting agricultural, domestic, and industrial demands, as well as maintaining ecosystem health. It also facilitates spatial and temporal analyses of water availability, helping to identify potential deficits or surpluses and guiding sustainable allocation and conservation strategies at the basin/sub-basin or district/sub-district level.

Using TRACE

Open TRACE on your browser (https://dms.iwmi.org/trace/). Click on ‘View TRACE Map’ (Figure 2) to open the toolbox page.



Next Generation Monitoring of Surface waTer fRom spACE

Integrated water monitoring to support science, policy, and communities.

Figure 2: TRACE toolbox. a is the TRACE landing page and b is the Overview of Storage assessment toolbox. Here, capitalised numbers in bold from A-G are the toolbox features explained in Toolbox Guide section.

Toolbox Guide

A: Assessment Unit selection: Hydrological Unit (Basin, Sub-basin, Watershed), Administrative Unit (State, District, Taluka), and Single Waterbody

B: Selection of waterbody size: All Waterbodies, Small (1-5 ha.), Medium (5-10 ha.), Large (10-50 ha.) and Very large (greater than 50 ha.)’

C: Date range selection

D: Additional layers selection: Landcover, Groundwater Storage, Terrestrial Water Storage

E: Background map toggle: Satellite and terrain

F: Legends for visible layers and transparency

E: Zoom adjustment

Assessment flows for Hydrological unit

Selecting the Assessment unit Ganga Basin

1. Locate the Basin Selection: At the top left of the map, click the dropdown menu (initially showing a blank area or a default selection).
2. Choose 'Ganga Basin': From the list that appears, click to select 'Ganga Basin'. The map will zoom in and highlight the entire Ganga Basin watershed in an orange overlay (as shown in figure 3).

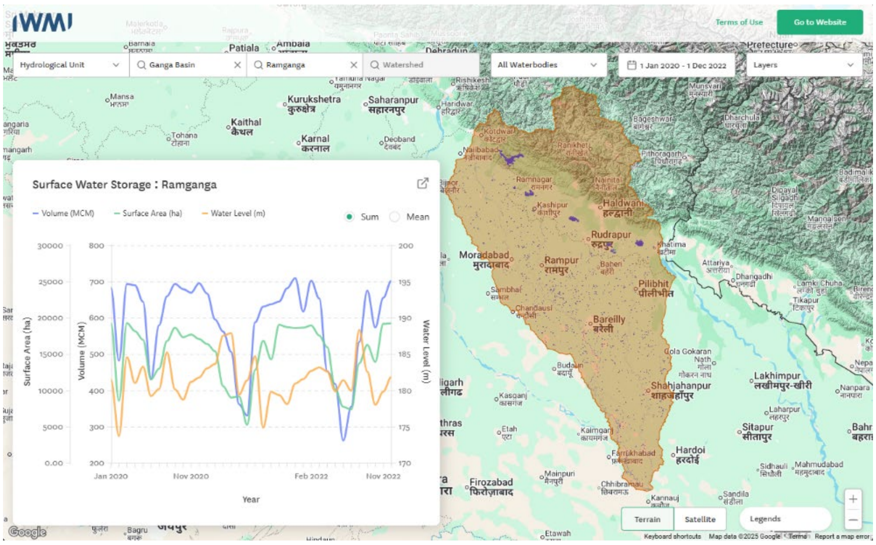


Figure 3: Sub-basin assessment. The interface features a spatial map highlighting water bodies within the hydrological unit and a synchronized time-series graph showing the relationship between Surface Area (ha), Volume (MCM), and Water Level (m) from 2020 to 2022.

Filtering Waterbodies

1. Access the Waterbodies Filter: Find the dropdown menu near the center top labelled 'All Waterbodies'.
2. Filter by Size: Click the dropdown as shown in figure 4, and then select 'Large Waterbodies' -Optional.
    - A chart on the left will update, displaying 'Water Storage (Ramganga)' data for large waterbodies within the selected area.

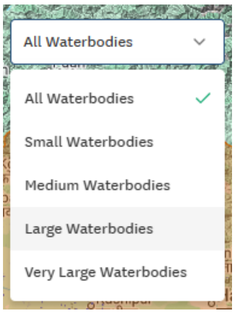


Figure 4: Drop-down selection menu for filtering water bodies by size. It allows users to aggregate statistics based on Small, Medium, Large, or Very Large water bodies.

Changing the Date Range

1. Open the Date Picker at the top right of the screen, as shown in figure 5 and click on the date range selector, which initially says '1 Jan 2020 - 1 Dec 2022'.
2. Optional -Select the Start Date: Click on the calendar icon and navigate to Jan 2021. Click on the 1st of January to set the new start date as shown in figure 6.
   - The date range will now update to '1 Jan 2021 - 31 Oct 2022'.
   - The chart data will update to reflect this new end date.

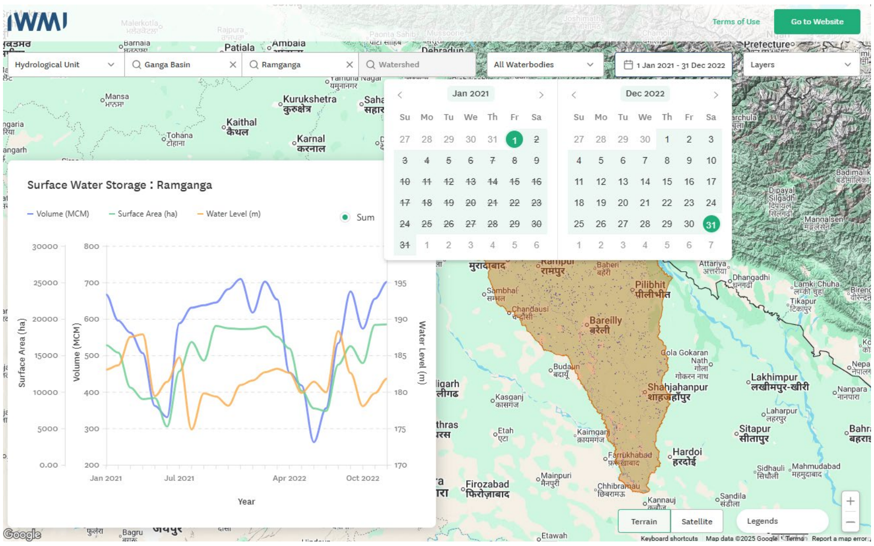


Figure 5: The date range picker interface in TRACE. Users can define specific start and end dates (e.g., January 2021 to December 2022) to filter earth observation data and update the storage trend graphs for the selected period.

Viewing Different Storage Layers

1. Open the Layers Menu: Click the 'Layers' menu button (figure 6) in the top right corner of the screen.

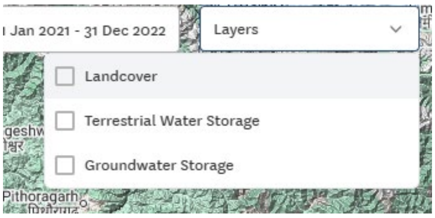


Figure 6: The "Layers" drop-down menu allows users to overlay auxiliary datasets onto the base map. Available options include Landcover, Terrestrial Water Storage, and Groundwater Storage, enabling a multi-dimensional view of the hydrological cycle within the selected basin

2. Enable Groundwater Storage:
    - In the Layers menu check the box for 'Groundwater Storage'.
    - The map will display a coloured grid showing groundwater storage anomalies across the watershed. (figure 7)
    - New chart will update with annual Groundwater annual replenishable water and surface water storage

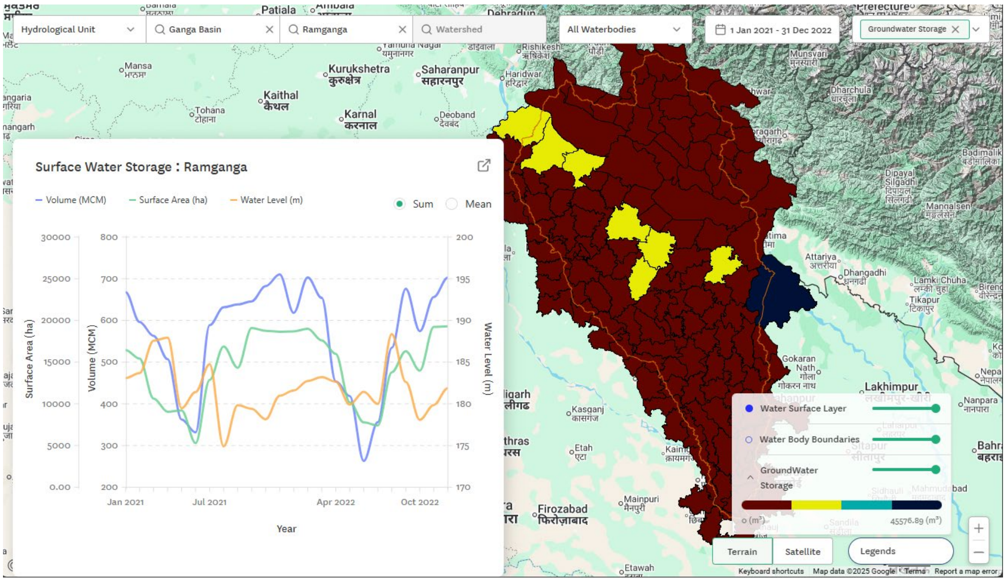


Figure 7: Spatial visualization of Groundwater Storage across the Ramganga basin. The map uses a color-coded thematic overlay to represent total annual replenishable water from Central Ground Water Board (CGWB), while the pop-up legend provides transparency controls for the Water Surface Layer and Water Body Boundaries to help correlate surface water with underground reserves.

3. Analyse Terrestrial Water Storage:
    - In the Layers menu, check the box for 'Terrestrial Water Storage'.
    - The map will update, and a new chart for 'Terrestrial Water Storage' will appear on the left (figure 8).

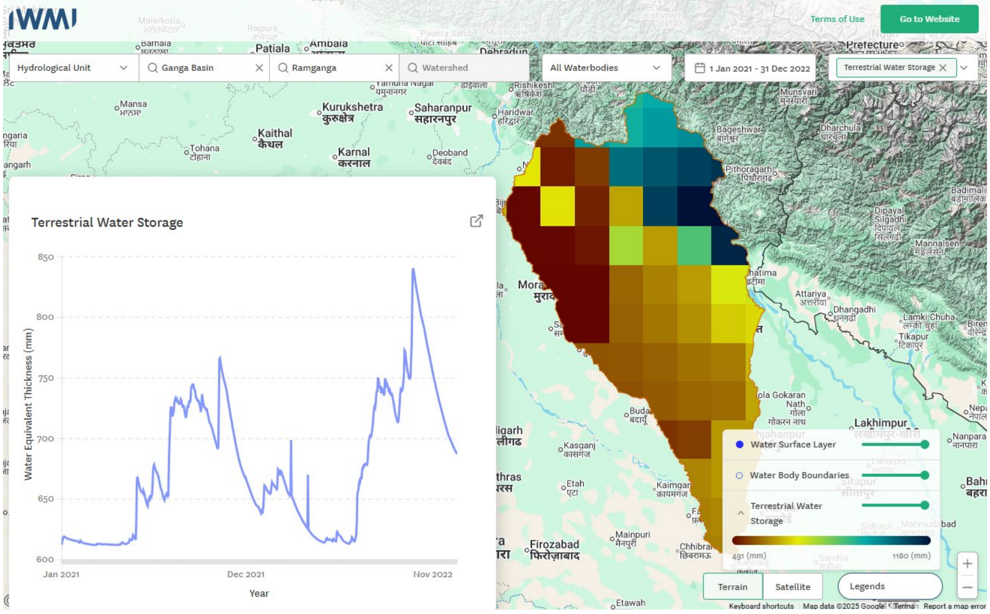


Figure 8: The Terrestrial Water Storage (TWS) view, showing the total water column variation (expressed in Water Equivalent Thickness in mm). The synchronized line graph tracks TWS fluctuations from January 2021 to November 2022, offering insights into the total water availability including soil moisture and groundwater.

Assessment flow for Administrative unit

Selecting the Administrative Unit

1. Change Unit Type: At the top left of the map, click the dropdown menu labelled 'Hydrological Unit'. Click on 'Administrative Unit' from the list. The filters will change from Basin/Sub-basin/Watershed to State/District/Taluka.
2. Click the 'State' dropdown and scroll down to select 'Uttar Pradesh’. The map will be overlaid with the district boundaries of Uttar Pradesh.
3. Click the 'District' dropdown and select 'Bareilly'. The map zooms in to the Bareilly district, highlighted with its sub-units.
4. Click the 'Taluka' dropdown and select 'Faridpur'. The map highlights the Faridpur Taluka in green (figure 9). A chart titled 'Surface Water Storage: Faridpur' automatically appears on the left, showing volume, surface area, and water level over time.

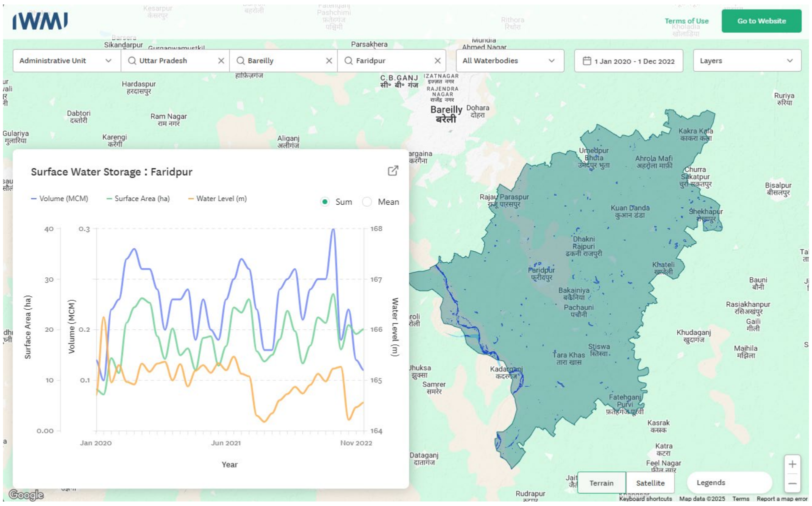


Figure 9: The TRACE interface filtered by Administrative Unit, specifically showing the Faridpur block within the Bareilly district. This view allows local authorities to assess water resources within political and management boundaries.

Viewing Water Storage Layers

1. Open the Layers Menu: Click the 'Layers' menu button in the top right corner of the screen. Enable Groundwater Storage by Check the box for 'Groundwater Storage'.
   - The map updates to display a coloured grid showing groundwater storage anomalies for the area as shown in figure 10.
   - A bar chart for 'Groundwater Storage and Surface Water Storage' appears below the surface water chart.

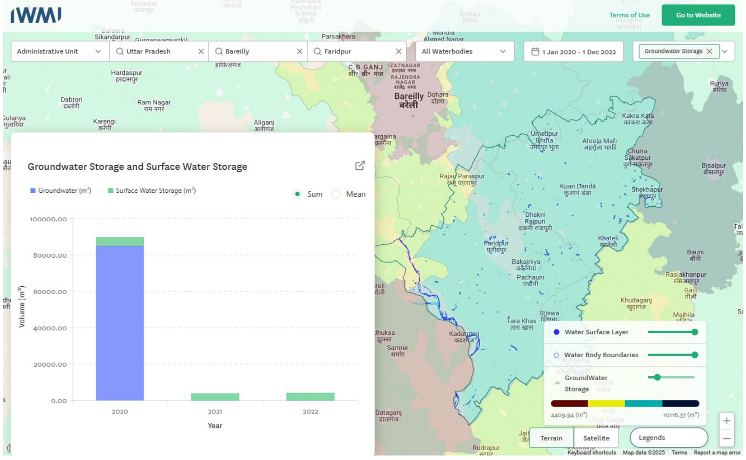


Figure 10: The TRACE interface displaying an integrated view of the Faridpur administrative block. This combines a spatial map highlighting local water body boundaries with a comparative bar chart showing Groundwater Storage (m^3) and Surface Water Storage (m^3) totals by year. The legend in the bottom right allows for interactive transparency adjustments of the spatial layers to visualize ground water storage of selected and adjacent districts.

2. Enable Landcover Layer:
   - In the Layers menu, check the box for 'Landcover'.
   - The map is overlaid with a detailed landcover classification (e.g., permanent water, forest, crops) as shown in figure 11.
   - Note: You can click the 'Legends' button in the bottom right to view the color key for the landcover types.

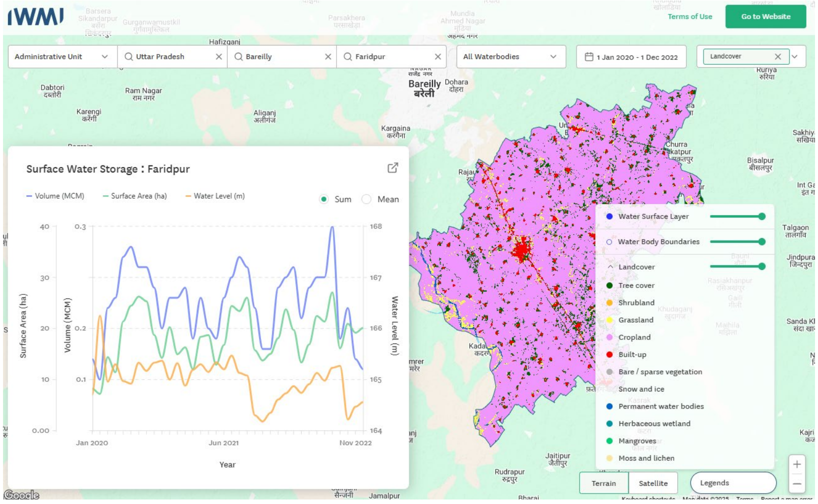


Figure 11: Spatial representation of landcover types within the Faridpur block, accessed via the Layers menu. The thematic overlay categorizes the landscape into classes, providing essential context for the proximity of water bodies to agricultural and urban areas. The active Legends panel in the bottom right enables users to interpret the color-coded classification and adjust layer transparency for enhanced spatial analysis.

3. Enable Terrestrial Water Storage:
   - Check the box for 'Terrestrial Water Storage'. As shown in figure 12, the map displays a color-coded representation of terrestrial water storage, and a time series chart for 'Terrestrial Water Storage' appears on the left.

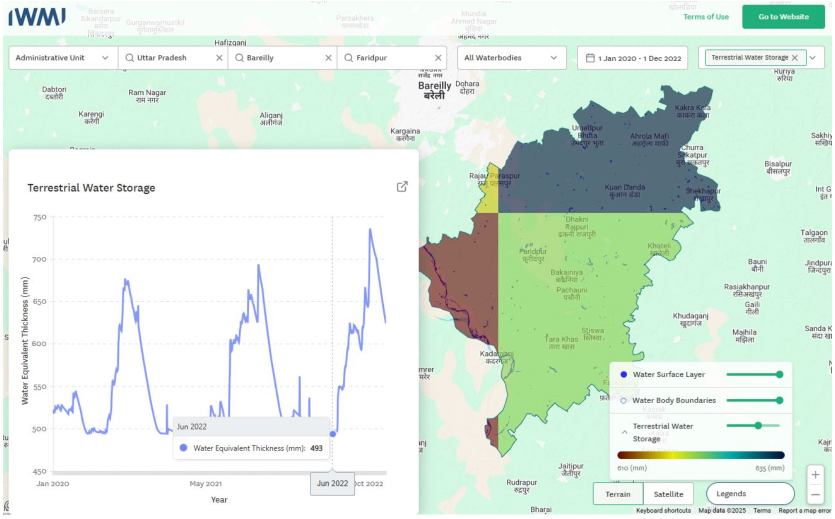


Figure 12: The interface with the Terrestrial Water Storage layer enabled for the Faridpur block. The spatial map displays a grid-based thematic overlay indicating total water column variations, while the left-hand panel provides a synchronized time-series chart of Water Equivalent Thickness (mm). This view allows users to identify specific temporal storage peaks, such as the 493 mm recorded in June 2022, providing a comprehensive look at water availability including soil moisture and groundwater

Assessment flow for single waterbody

Selecting a Single Water Body

1. Change Unit Type: At the top left of the map, click the dropdown menu labelled 'Administrative Unit' (or your last selected unit). Click on 'Water Body' from the list. The filter controls will change to a single dropdown for selecting the water body.
    - Search/Select Water Body: Click the water body in the map. The map will zoom in to the selected waterbody location
    - Chart titled 'Surface Water Storage' will appear on the left, displaying surface area, volume, and water level over time.

Analysing Data on the Map and Chart

1. View Individual Data Points: Move your cursor over the time series chart on the left
2. Inspect Date-Specific Data: As you hover over the chart, specific date and measured value (Volume in BCM) will be displayed in a tooltip (figure 13).

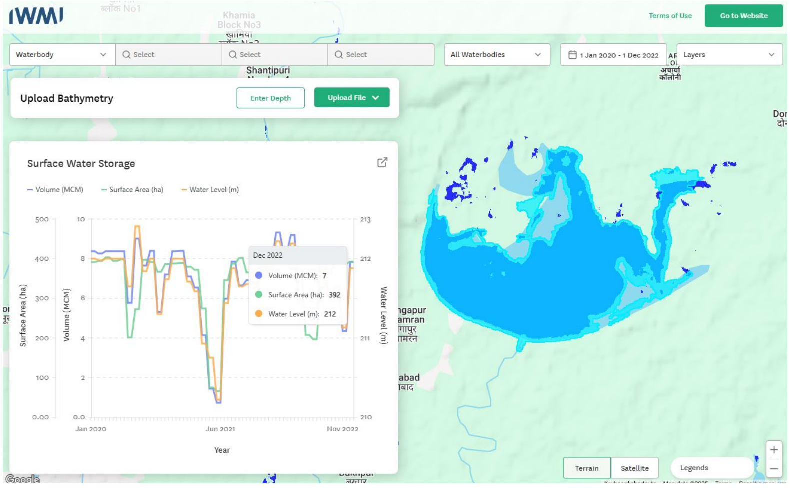
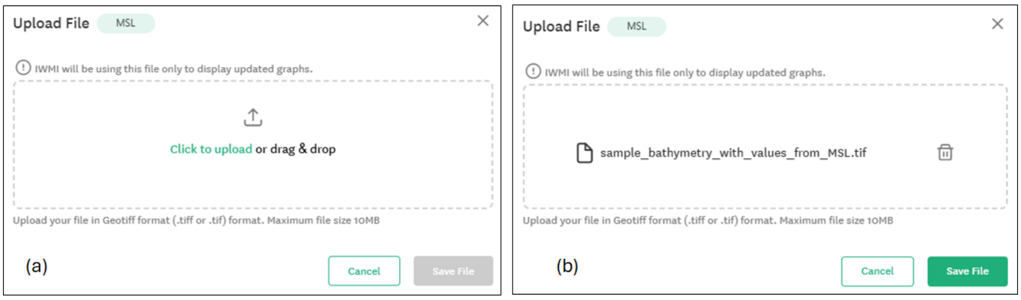


Figure 13: The TRACE interface after selecting the 'Water Body' unit type. The spatial view focuses on a specific reservoir, while the left-hand panel generates a Surface Water Storage chart. The figure demonstrates the interactive tooltip feature, where hovering over the time-series graph reveals precise data points,such as the 7 MCM Volume, 392 ha Surface Area, and 212 m Water Level recorded in December 2022, allowing for granular temporal inspection of the selected water body.

Custom Bathymetry

1. You can upload your bathymetric data if you have into the toolbox to estimate volume and water level. You can upload bathymetric data which has to be a geotiff either relative units or height from mean sea level. Check figure 14 for more understanding of the uploading.



ⓘ IWMI will be using this file only to display updated graphs.

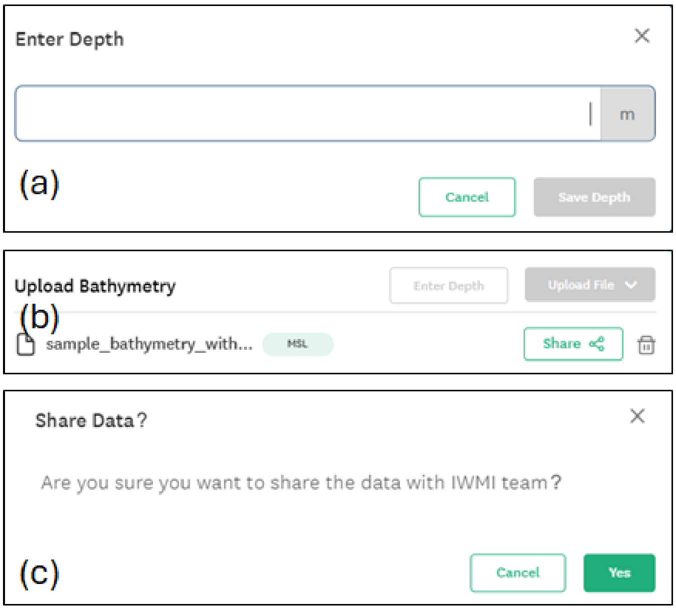
Upload your file in Geotiff format (.tiff or .tif) format. Maximum file size 10MB

sample_bathymetry_with_values_from_MSL.tif

Figure 14: The TRACE bathymetry integration workflow showing (a) the initial upload modal for GeoTIFF files (up to 10MB) and (b) the confirmation of a selected file, such as height data from Mean Sea Level (MSL). Once saved, the tool uses this custom data to automatically update the Surface Water Storage graphs, ensuring more accurate volume and water level estimations for the specific water body.

2. If you have information of maximum depth of the waterbody, you can enter the value in meters using ‘Enter Depth’. It will be used to generate bathymetry layer by method mentioned in the methodology section. Check figure 15 for visual steps.

   Note: Once page is closed or you refresh the page, uploaded data is deleted from toolbox, but you can share the data using share button.



sample_bathymetry_with...

Are you sure you want to share the data with IWMI team?

Figure 15: Advanced features of the custom bathymetry toolbox: (a) the Enter Depth modal used to input the maximum depth (meters) for generating a bathymetry layer based on system methodology; (b) the dashboard view showing the successfully added file with a Share option; and (c) the Share Data confirmation dialog, which allows users to persist their uploaded data by sharing it with the IWMI team before the session is closed or refreshed.

References

Alsdorf, D. E., Rodríguez, E., & Lettenmaier, D. P. (2007). Measuring surface water from space. *Reviews of Geophysics*, *45*(2). https://doi.org/10.1029/2006RG000197

Bouma, J. A., Biggs, T. W., & Bouwer, L. M. (2011). The downstream externalities of harvesting rainwater in semi-arid watersheds: An Indian case study. *Agricultural Water Management*, *98*(7), 1162–1170. https://doi.org/https://doi.org/10.1016/j.agwat.2011.02.010

Donchyts, G., Winsemius, H., Baart, F., Dahm, R., Schellekens, J., Gorelick, N., Iceland, C., & Schmeier, S. (2022). High-resolution surface water dynamics in Earth's small and medium-sized reservoirs. *Scientific Reports*, *12*(1). https://doi.org/10.1038/s41598-022-17074-6

Gao, H., Birkett, C., & Lettenmaier, D. P. (2012). Global monitoring of large reservoir storage from satellite remote sensing. *Water Resources Research*, *48*(9). https://doi.org/10.1029/2012WR012063

Holtgrave, A.-K., Röder, N., Ackermann, A., Erasmi, S., & Kleinschmit, B. (2020). Comparing Sentinel-1 and -2 Data and Indices for Agricultural Land Use Monitoring. *Remote Sensing*, *12*(18). https://doi.org/10.3390/rs12182919

Khazaei, B., Read, L. K., Casali, M., Sampson, K. M., & Yates, D. N. (2022). GLOBathy, the global lakes bathymetry dataset. *Scientific Data*, *9*(1). https://doi.org/10.1038/s41597-022-01132-9Liebe, J., van de Giesen, N., & Andreini, M. (2005). Estimation of small reservoir storage capacities in a semi-arid environment. *Physics and Chemistry of the Earth*, *30*(6-7 SPEC. ISS.), 448–454. https://doi.org/10.1016/j.pce.2005.06.011

Massuel, S., Perrin, J., Mascre, C., Mohamed, W., Boisson, A., & Ahmed, S. (2014). Managed aquifer recharge in South India: What to expect from small percolation tanks in hard rock? *Journal of Hydrology*, *512*, 157–167. https://doi.org/https://doi.org/10.1016/j.jhydrol.2014.02.062McCartney, M., & Smakhtin, V. (2010). *Water storage in an era of climate change: addressing the challenge of increasing rainfall variability. Blue paper.* https://doi.org/10.5337/2010.012

Ministry Of Jal Shakti. (2023). *Waterbodies first Census Report Volume - 1*. https://cdnbbsr.s3waas.gov.in/s3a70dc40477bc2adceef4d2c90f47eb82/uploads/2023/04/2023040672.pdf

Mitchard, E. T. A., Saatchi, S. S., White, L. J. T., Abernethy, K. A., Jeffery, K. J., Lewis, S. L., Collins, M., Lefsky, M. A., Leal, M. E., Woodhouse, I. H., & others. (2012). Mapping tropical forest biomass with radar and spaceborne LiDAR in Lopé National Park, Gabon: overcoming problems of high biomass and persistent cloud. *Biogeosciences*, *9*(1), 179–191.

Nasirzadehdizaji, R., Balik Sanli, F., Abdikan, S., Cakir, Z., Sekertekin, A., & Ustuner, M. (2019). Sensitivity Analysis of Multi-Temporal Sentinel-1 SAR Parameters to Crop Height and Canopy Coverage. *Applied Sciences*, *9*(4). https://doi.org/10.3390/app9040655

NRSC (ISRO). (n.d.). *Bhuvan Water bodies Information System*. Retrieved July 26, 2023, from https://bhuvan-wbis.nrsc.gov.in/

NWIC. (n.d.). *India Water Resources Information System (India WRIS)*. Retrieved August 31, 2023, from https://indiawris.gov.in

Ogilvie, A., Belaud, G., Massuel, S., Mulligan, M., le Goulven, P., & Calvez, R. (2018). Surface water monitoring in small water bodies: Potential and limits of multi-sensor Landsat time series. *Hydrology and Earth System Sciences*, *22*(8), 4349–4380. https://doi.org/10.5194/hess-22-4349-2018

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