

Remote Sensing Approaches for Freshwater Assessment in Islands of the Indo-Pacific Region

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Abstract

Groundwater is the main freshwater source for most Pacific islands, yet these thin freshwater lenses are highly vulnerable to sea level rise, saltwater intrusion, storm surges, and prolonged drought. Field campaigns are essential for understanding groundwater dynamics, but they remain sparse. This report assesses the use of remote sensing in evaluating groundwater quantity and quality on small islands, and examines how models paired with field data can close key information gaps. Satellites do not directly detect freshwater lenses or salinity, but they offer proxies such as vegetation stress and surface wetness that relate to groundwater conditions. Optical imagery from Sentinel-2 and Landsat shows changes in vegetation condition and surface wetness that reflect groundwater stress, while Planet imagery adds finer spatial detail along narrow coastlines and small islands but has limited coverage outside the tropics and lower spectral resolution. Radar and thermal sensors contribute additional information on inundation, soil moisture, and coastal discharge, yet their pixel sizes, revisit intervals, and positional accuracy often exceed the dimensions of small islands, which makes it difficult to separate true hydrologic change from noise. Gravimetric satellites provide information on regional water storage but cannot resolve the thickness or salinity of freshwater lenses at the scale required for island-level analysis. Airborne electromagnetic surveys are the only remote method that can directly map freshwater lens thickness and salinity with the resolution needed for island-scale groundwater assessment. However, their high cost, logistical demands, and reliance on calibration data make them impractical for regional monitoring, limiting their use to targeted assessments on specific islands. While remote sensing cannot replace field data, it can extend their reach. When paired with in-situ data and simplified models, it enables practical estimates of lens thickness, recharge response, and salinization risk. These models draw on high-resolution spatial inputs such as island morphology, shoreline geometry, elevation, salinity, and soil moisture, all of which are increasingly accessible. Together, these tools can support efforts to identify freshwater risks, prioritize monitoring, and improve groundwater management on vulnerable island systems.

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Executive Summary

Groundwater Challenges in the islands of the Indo-Pacific Region

The islands of the Indo-Pacific region encompass one of the most geographically dispersed and hydrologically fragile collections of islands in the world. Across Micronesia, Polynesia, Melanesia, and U.S.-affiliated Pacific territories, local communities and operational installations depend almost entirely on thin freshwater lenses—narrow layers of freshwater floating atop denser saline groundwater—to meet basic water needs. These lenses are small in volume, highly sensitive to environmental change, and replenished only through rainfall. Increasingly, they are failing under pressure from saltwater intrusion, storm surges, sea-level rise, prolonged dry periods, and land use change. The challenge is both hydrological and operational: understanding where groundwater is available, where it is declining, and how that will affect mission readiness and regional resilience.

Despite their critical role, groundwater systems on most islands remain poorly understood. In-situ measurements are rare, and many of the smallest islands have never been assessed for groundwater availability, recharge, or quality. Traditional hydrogeological surveys are logistically and financially prohibitive in this context, requiring field access, instrumentation, and long-term monitoring that is infeasible across hundreds of remote, jurisdictionally fragmented locations. This data gap is not just a technical shortfall; it is a fundamental barrier to making informed, proactive decisions about infrastructure, security, logistics, and environmental health in the Pacific.

Data Gaps and the Role of Remote Sensing

Global remote sensing and environmental datasets have expanded dramatically, enabling routine monitoring of rainfall, vegetation stress, soil moisture, and topography. For small island contexts, however, these products are often used outside their design scale. Spatial resolution is frequently too coarse, revisit can be sparse during critical events, and modeling assumptions are not tailored to atoll hydrogeology. Most importantly, no satellite sensor directly detects freshwater lenses on small islands. Optical and radar signals are indirect indicators of stress such as vegetation condition, surface wetness, inundation, and ground motion, not maps of lens geometry.

Airborne Electromagnetics (AEM) is the principal geophysical exception. When flown, AEM can resolve lens thickness and salinity structure at actionable depths and spatial resolution, producing decision grade maps that satellites cannot. Its use is constrained by cost, aircraft and permitting requirements, coastal coupling effects, and the need for calibration with wells or conductivity profiles. AEM is best applied selectively to verify lens presence, estimate storage, and bound uncertainty at high priority sites identified by satellite screening.

A Targeted Modeling Approach Using Open Datasets

This report was developed to bridge that gap. It provides a targeted assessment of how remote sensing and global datasets can be systematically used to evaluate groundwater potential,

freshwater lens stability, and environmental stress in small island systems across the Indo-Pacific region. Rather than offering an exhaustive catalog of all possible data sources, the report focuses on those with the highest utility for practical, scalable assessments: datasets that are freely accessible, updated regularly, regionally complete, and spatially or thematically aligned with island-scale hydrology.

The core contribution of the report is the development and application of a simplified freshwater lens model that can be implemented across hundreds of islands with minimal input requirements. The model is based on well-established hydrologic principles and adapted to function with inputs drawn entirely from open-source global datasets. It estimates key groundwater indicators such as lens thickness, freshwater volume, and sensitivity to drought or salinity intrusion. These outputs are designed to support triage-style assessments—ranking islands by vulnerability, identifying locations that may already be experiencing stress, and highlighting where monitoring or mitigation investments should be prioritized.

Remote sensing indices play a central role in this approach. Among those evaluated, the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Moisture Index (NDMI) emerge as particularly valuable. Both have been shown to detect vegetation stress linked to declining freshwater availability and salinization, especially in tropical and subtropical island environments where shallow-rooted vegetation is closely tied to groundwater. NDVI tracks greenness and overall plant health, while NDMI responds more directly to moisture content, making it highly sensitive to subsurface deficits. These indices, derived from sensors such as Landsat and Sentinel-2, are available at spatial resolutions that can capture intra-island variation and are well-suited for early-warning applications.

Other indices—such as the Modified Normalized Difference Water Index (MNDWI) and the Soil-Adjusted Vegetation Index (SAVI)—have more limited applicability but can be useful in specific contexts, such as coastal urban areas or arid atolls with sparse vegetation. However, they do not serve as reliable proxies for subsurface freshwater dynamics and should be treated as supplementary indicators. NDVI and NDMI should be prioritized in future remote sensing-based assessments of groundwater risk in island settings.

Toward Scalable, Actionable Groundwater Assessments

To support the freshwater lens model, the report identifies five global datasets that together provide a minimal but sufficient input package for consistent regional analysis. These are:

- First, the Geoscience Australia Island Groundwater Dataset, which compiles measured lens characteristics (e.g., thickness, salinity profiles) from field surveys across Pacific islands. This dataset provides rare and valuable ground-truth data for calibration and model validation.
- Second, the Global Island Explorer (GIE), which offers high-resolution spatial boundaries and attributes for over 340,000 islands globally, including maximum island width—an essential parameter for lens geometry estimation.

- Third, GEOMORPHO90 and GLO-30 digital elevation models, which provide consistent elevation data at 30-meter or finer resolution and enable the estimation of slope, recharge potential, and hydrotype classification.
- Fourth, the CHIRPS rainfall archive and the SPI-12 drought index, which supply long-term precipitation and drought data needed to assess recharge conditions and hydroclimatic variability. These are particularly useful for detecting multi-year trends and extreme dry periods associated with ENSO cycles.
- Fifth, SMAP soil moisture data and MODIS-derived evapotranspiration (ET) layers, which offer dynamic indicators of surface wetness and water fluxes, serving as indirect proxies for groundwater recharge and stress.

Together, these datasets enable a robust, repeatable, and scalable workflow that can be deployed across large spatial extents. They are hosted on public platforms, compatible with cloud-based processing tools, and supported by extensive documentation. The report presents a complete template for applying them in combination, from data acquisition and preprocessing to modeling and interpretation.

While global groundwater datasets such as GRACE or GLOBGM offer valuable insights at continental or basin scales, the report finds that they are unsuitable for most islands in the Indo-Pacific region due to their coarse resolution. These products may still provide useful background context or regional trends but should not be used as the basis for island-scale decision-making.

The value of the approach developed here lies in its adaptability and operational relevance. It can be scaled to cover entire archipelagos, refined to focus on particular islands of interest, or automated to run periodically as new data are released. The report avoids prescribing fixed thresholds or outputs; instead, it provides the structure for a modular, transparent, and evolving groundwater monitoring system that can be adapted as new priorities or data emerge.

In delivering a method that functions without fieldwork, this report provides a pathway for making informed decisions in places where conventional hydrologic analysis is infeasible. It allows planners and decision-makers to quantify groundwater potential, compare vulnerabilities, and allocate resources strategically across the Indo-Pacific region. As the climate continues to shift and resource pressures mount, such capacity will be essential not only for environmental resilience but also for maintaining operational continuity and regional stability.

This work is intended as a foundation. Further refinements, including integration with infrastructure datasets, land cover change detection, and stakeholder feedback, are encouraged. However, the core finding remains: with a focused set of tools and a practical model structure, it is now possible to conduct systematic groundwater assessments across small island environments using only globally available remote sensing and geospatial data.

1: Remote sensing optical sensors for groundwater monitoring

1.1 PlanetScope (Planet Labs)

Technical Overview

PlanetScope is a constellation of nanosatellites operated by Planet Labs, delivering daily global coverage with a spatial resolution of 3–5 meters. It captures four bands—Blue, Green, Red, and Near-Infrared (NIR)—with data availability beginning in 2016. For tropical regions, including many small islands in the Indo-Pacific region, imagery is available freely through the NICFI program, making it a practical resource for operational and research purposes (Figure 1).

Key Variables Relevant to Groundwater

PlanetScope's high spatial and temporal resolution makes it well-suited for detecting surface indicators of groundwater dynamics in small island environments. In particular, the platform is valuable for monitoring coastal water turbidity, which can signal interactions between groundwater and nearshore marine systems. High-frequency imagery allows for the detection of temporal anomalies in water quality that may be linked to subsurface discharge, nutrient loading, or freshwater lens instability. PlanetScope can also support assessments of algal bloom formation and spatial changes in coastal ecosystems, offering a useful tool for understanding the surface expressions of groundwater-related processes where in situ monitoring is limited or infeasible.

While PlanetScope has not yet been applied to groundwater-related studies in the Indo-Pacific region specifically, and its archive only extends back to 2016, its capabilities for high-frequency monitoring make it promising for island-scale hydro-ecological research. Although the sensor lacks shortwave infrared bands, it can be used to compute vegetation- and moisture-sensitive indices such as NDVI, NDMI, NDWI, and others. These indices have been widely used to infer vegetation stress due to salinization, freshwater lens depletion, and drought in other contexts. While these applications have yet to be validated using PlanetScope in tropical island systems, they represent a clear methodological potential. A full list of applicable indices and their formulas is provided in Table 3.

Usefulness for Groundwater Scope

The combination of daily temporal resolution, sub-5 m spatial detail, and tropical-region access through NICFI make PlanetScope one of the most powerful tools for monitoring small-scale groundwater-related dynamics in the Indo-Pacific region. It is particularly well-suited for fine-grained coastal changes, vegetation degradation, and shallow water quality monitoring—all key indicators of groundwater stress or salinity shifts on small islands.

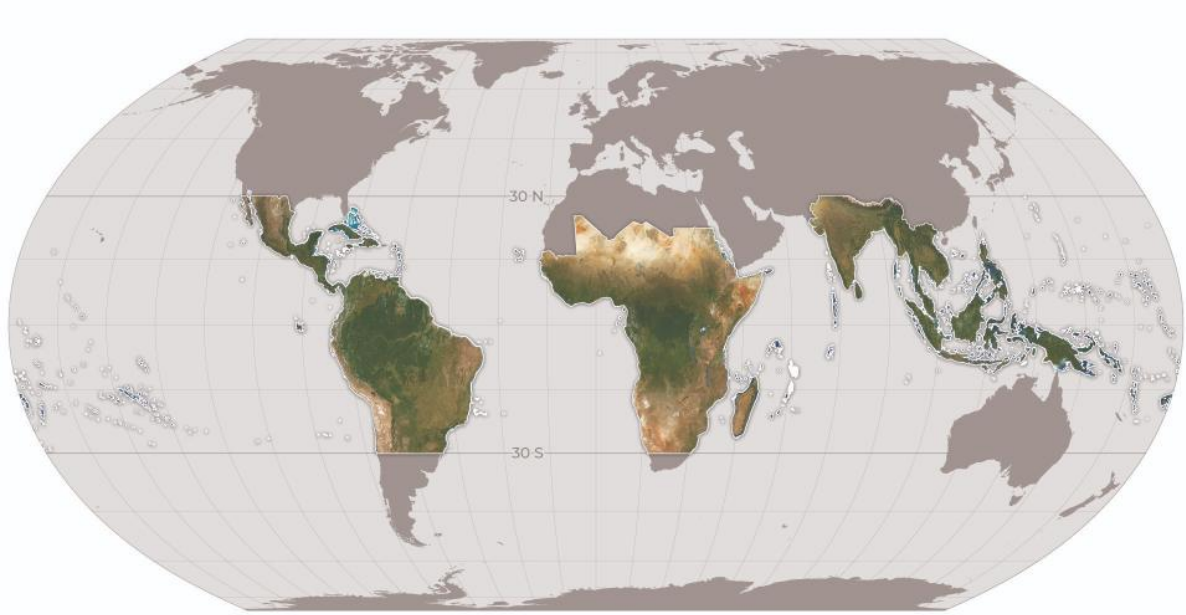


Figure 1: The Norway's International Climate & Forests Initiative (NICFI) program that provides access to Planet's high-resolution, analysis-ready mosaics of the world's tropics.
Source: https://university.planet.com/page/nicfi

1.2 WorldView (Maxar Technologies)

Technical Overview

WorldView satellites, including WorldView-2 and WorldView-3, are operated by Maxar Technologies and provide some of the highest commercially available spatial resolution for Earth observation (Figure 2). WorldView-3, in particular, captures imagery at 0.31 m (panchromatic), 1.24 m (multispectral), and 3.7 m (shortwave infrared - SWIR) resolutions with a revisit time of less than one day. The satellite carries 29 spectral bands including visible, near-infrared, and SWIR, enabling detailed surface feature detection and water content analysis. WorldView data has been commercially available since 2014 and is priced at a premium—costs can range from $20–30 per km², with even higher fees for archive or tasking requests. Given the vast size and

geographic dispersion of the Indo-Pacific region, comprehensive coverage using WorldView imagery would incur significant costs and data processing requirements.

Key Variables Relevant to Groundwater

WorldView's sub-meter resolution and access to SWIR bands provide the ability to monitor several variables relevant to groundwater dynamics on small islands. The sensor enables detailed mapping of surface features associated with saltwater intrusion or groundwater-fed coastal features, including vegetated wetlands and seepage zones. The inclusion of SWIR bands allows for enhanced detection of soil moisture gradients and vegetation stress, including salt stress and drought-related degradation—key indicators of shallow freshwater lens health. In coastal environments, WorldView imagery can support bathymetric modeling in shallow clear-water zones, indirectly helping to identify areas of submarine groundwater discharge (SGD) where depth anomalies or discoloration may appear. However, while these capabilities exist, peer-reviewed groundwater-specific applications of WorldView in the Indo-Pacific region are extremely limited, and published studies primarily focus on small-scale case studies or general coastal mapping outside of this geographic scope.

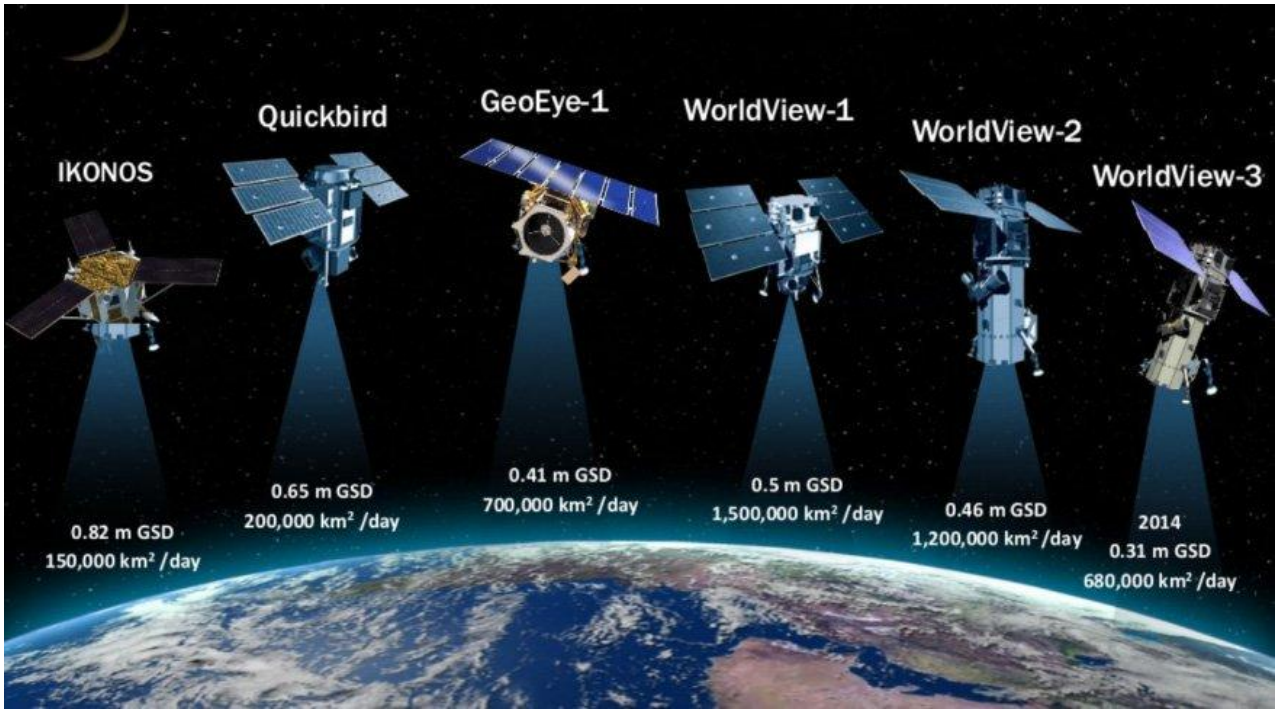


Figure 2: Maxar's constellation of high-resolution satellites and sensors. Source: https://microsites.maxar.com/

Usefulness for Groundwater Scope

Limited. Despite its high spatial and spectral precision, WorldView is constrained by significant cost, limited open access, and large data volumes that pose logistical barriers for regional-scale or time-series analyses across the Indo-Pacific region. Its best use lies in targeted, site-specific studies, such as detailed mapping of salt-stressed vegetation, identification of SGD zones, or change detection in high-priority coastal aquifers. As a standalone solution for regional monitoring, however, its applicability is limited.

1.3 Sentinel-2 (European Space Agency)

Technical Overview

Sentinel-2 is a twin-satellite mission operated by the European Space Agency (ESA) under the Copernicus Programme, comprising Sentinel-2A and Sentinel-2B, launched in June 2015 and March 2017, respectively. The satellites are positioned in the same sun-synchronous orbit, phased 180° apart, enabling a revisit time of 5 days at the equator and more frequent coverage at higher latitudes. Each satellite carries a MultiSpectral Instrument (MSI) that captures imagery in 13 spectral bands, spanning from the visible and near-infrared (VNIR) to the shortwave infrared (SWIR) regions. Spatial resolution varies by band: 10 meters for four VNIR bands, 20 meters for six red-edge and SWIR bands, and 60 meters for three atmospheric correction bands. The MSI provides a swath width of 290 km, enabling broad regional coverage. Sentinel-2 data is freely available through the Copernicus Open Access Hub, with an archive beginning in 2015, supporting long-term and large-area monitoring in the Indo-Pacific region.

Key Variables Relevant to Groundwater

Sentinel-2's multispectral capabilities and frequent revisit interval make it well-suited for monitoring indicators of groundwater dynamics on small islands. The inclusion of SWIR bands enhances detection of soil and vegetation moisture, both critical for assessing freshwater lens degradation, saltwater intrusion, and drought-induced salinization. For example, indices such as the Normalized Difference Moisture Index (NDMI) and Normalized Difference Water Index (NDWI) are frequently used to monitor moisture anomalies and surface water changes. The red-edge bands are especially useful for detecting early-stage vegetation stress, which may signal salinity impacts on shallow-rooted ecosystems dependent on groundwater. While Sentinel-2 has not yet been widely applied in published groundwater studies specific to the Indo-Pacific region,

it has been successfully used in similar coastal tropical environments to detect hydrologic stress. A wide range of spectral indices relevant to groundwater potential, quality, and salinity—including NDVI, NDWI, NDMI, NDSSI, and NSMI—can be derived from Sentinel-2 imagery. See Table 3 for a comprehensive summary of applicable indices and formulas.

Usefulness for Groundwater Scope

Good. Sentinel-2 offers a strong combination of moderate resolution, frequent revisit (5 days), and free open access, which makes it particularly valuable for tracking temporal changes in indicators such as vegetation stress, surface moisture, and coastal water clarity across small islands. These are all indirect proxies for groundwater quality and freshwater lens integrity. Sentinel-2's broad swath allows full island chains or archipelagos to be monitored cost-effectively. However, several challenges limit its utility for small islands in the Indo-Pacific: (1) persistent cloud cover in the tropics reduces usable imagery frequency, (2) moderate spatial resolution (10–20 m) may not resolve narrow freshwater lenses or inland water bodies typical of atolls, and (3) no thermal band means groundwater discharge zones cannot be detected via surface temperature anomalies. Despite these limitations, Sentinel-2 remains a reliable and scalable option for multi-temporal groundwater-related monitoring, especially when combined with ancillary datasets or machine learning classifiers.

1.4 Landsat 8/9 (NASA/USGS)

Technical Overview

Landsat 8 (launched in 2013) and Landsat 9 (launched in 2021) are part of NASA and USGS's long-running Landsat program, which offers the most extensive continuous record of Earth observation globally. Each satellite carries the Operational Land Imager (OLI) and the Thermal Infrared Sensor (TIRS), capturing 11 spectral bands, including visible, near-infrared, shortwave infrared, and thermal infrared wavelengths. Spatial resolution is 30 meters for most bands and 100 meters (resampled to 30 m) for thermal. Revisit time is 16 days per satellite, effectively halved to 8 days when both are operational. Data is freely available through the USGS EarthExplorer and Google Earth Engine, with an uninterrupted archive dating back to 1984.

Key Variables Relevant to Groundwater

Landsat's inclusion of thermal infrared (TIR) bands enables direct detection of submarine groundwater discharge (SGD) via coastal thermal anomalies. This is especially valuable in tropical island environments where freshwater seeps into warmer marine waters. Landsat TIR has been successfully used to map SGD zones in atoll and reef environments. Additionally, Landsat imagery supports derivation of vegetation moisture and salinity indices, such as NDMI, NDWI, and NDSSI, which are sensitive to stress caused by saltwater intrusion and freshwater lens depletion. The long temporal archive makes Landsat ideal for detecting long-term trends in vegetation degradation linked to changing groundwater quality. These indices are fully compatible with Landsat data—see Table 3 for details.

Usefulness for Groundwater Scope

Good. Landsat offers a unique advantage for groundwater-related monitoring due to its long archive, free availability, and inclusion of thermal infrared bands, which are absent from most other freely available optical sensors. It is especially valuable for detecting submarine groundwater discharge, tracking salt stress over time, and examining drought impacts on freshwater lenses. However, its moderate spatial resolution (30 m) limits its ability to resolve small freshwater bodies or narrow coastal zones typical of many Indo-Pacific islands. Persistent cloud cover also reduces usable observations in tropical regions. Still, Landsat remains one of the most proven, scalable platforms for historical and synoptic-scale groundwater assessments.

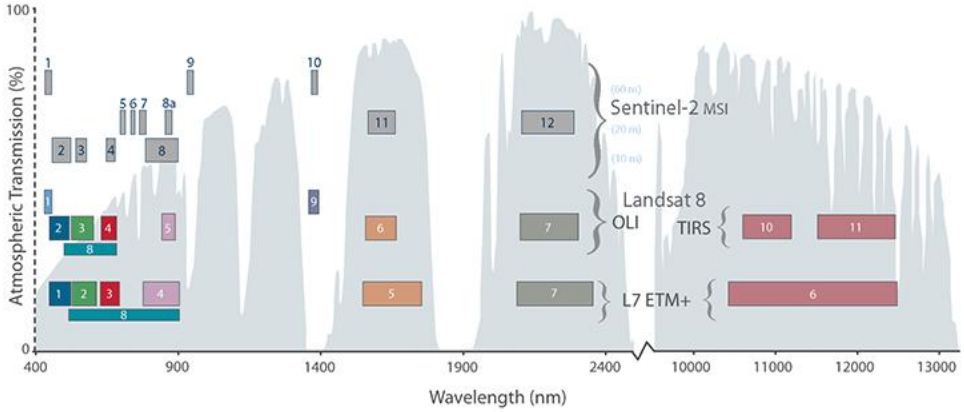


Figure 3: Comparison of Landsat 7 and 8 bands with Sentinel-7.
Source: https://landsat.gsfc.nasa.gov/

1.5 MODIS (NASA)

Technical Overview

The Moderate Resolution Imaging Spectroradiometer (MODIS) is an optical sensor aboard NASA's Terra (launched in 1999) and Aqua (launched in 2002) satellites. It captures imagery in 36 spectral bands across the visible to thermal infrared spectrum. Spatial resolution is 250 m for red and NIR bands, 500 m for additional VIS/NIR/SWIR bands, and 1,000 m for thermal and atmospheric bands. MODIS provides daily global coverage with a swath width of 2,330 km, and its extensive archive supports two decades of continuous Earth observation. Data is freely available from NASA's Earthdata portal and Google Earth Engine.

Key Variables Relevant to Groundwater

MODIS has been widely used to track land surface temperature, vegetation stress, and regional drought conditions, all of which can reflect groundwater availability or pressure on freshwater lenses at broad scales. The thermal infrared bands allow for detection of surface temperature anomalies potentially associated with submarine groundwater discharge (SGD), though only in large coastal systems due to spatial limitations. MODIS-derived indices like NDVI, NDWI, and NDMI are useful for detecting regional vegetation moisture patterns and stress from salinity or lens depletion—but their utility is constrained by the coarse resolution. These indices are fully compatible with MODIS data (see Table 3), and are often used in combination with higher-resolution sensors for downscaling.

Usefulness for Groundwater Scope

Limited. MODIS is not suitable for monitoring groundwater-related processes at the island scale, as its coarse spatial resolution (250–1,000 m) cannot resolve fine-scale coastal features, small freshwater lenses, or narrow vegetation gradients that typify most small islands in the Indo-Pacific region. However, it remains useful for regional pattern detection, particularly for tracking broad hydroclimatic trends, drought severity, or thermal anomalies across archipelagos or clusters of islands. MODIS may also be effective when used in fusion with higher-resolution data for modeling groundwater impacts on vegetation or surface temperature.

Table 1: Primary data from optical remote sensing

Satellite / Mission	Key Variables	Resolution	Usefulness for Small Islands	Reference Example
PlanetScope (Planet Labs)	Vegetation health, soil moisture proxies, water quality	3–5 m / daily	Excellent: High-resolution and frequency & free in the tropics	e.g. Li et al. 2022. Shallow coastal water turbidity monitoring using Planet Dove satellites. doi: 10.1002/rse2.259
WorldView (Maxar)	NDVI, EVI, surface features	≤1 m / 2–3 days	Limited: Very high detail, but expensive	e.g. Cao et al. 2019. Shallow water bathymetry from WorldView-2 stereo imagery https://doi.org/10.1080/22797254.2019.1658542 Hakim et al. 2018. demonstrates the utility of high-resolution satellite imagery in coastal and nearshore studies, which can be relevant for understanding submarine groundwater discharge areas. DOI 10.1088/1755-1315/165/1/012027
Sentinel-2 (ESA)	NDVI, EVI, NDWI, soil/vegetation moisture	10–20 m / 5 days	Good: Free, high revisit, useful for tracking stress	Kwong et al. 2022 - Automatic Mapping and Monitoring of Marine Water Quality Parameters https://doi.org/10.3389/fmars.2022.871470 Caballero et al. 2022. Water quality monitoring. https://doi.org/10.1016/j.scitotenv.2022.153433
Landsat 8/9 (NASA/USGS)	NDVI, EVI, TIR for groundwater discharge	30 m / 16 days	Good: Long-term monitoring and TIR applications	Caineta et al., 2022 – Submarine groundwater discharge detection. https://doi.org/10.1016/j.rse.2022.113109 Carruthers et al., 2024 – Mangrove dieback linked to saltwater intrusion on Maldives atolls using Landsat. https://doi.org/10.1038/s41598-024-73776-z
MODIS (NASA)	TIR for surface temp, vegetation stress	250–1,000 m / Daily	Limited: Coarse, but useful for synoptic regional trends	USGS, 2023 – Vegetation and Water Monitoring Datasets for selected locations in the Republic of the Marshall Islands from 2017-2022

2: Active Remote Sensing for Groundwater Monitoring

2.1 Sentinel-1 (European Space Agency)

Technical Overview

Sentinel-1 is a twin-satellite Synthetic Aperture Radar (SAR) mission by the European Space Agency, consisting of Sentinel-1A (launched in 2014) and Sentinel-1B (2016–2022). Operating in the C-band (5.405 GHz), Sentinel-1 provides 10 m spatial resolution in Interferometric Wide (IW) swath mode and a 6–12 day revisit cycle. It is capable of imaging under all weather and lighting conditions, and data is freely available via the Copernicus Open Access Hub.

Key Variables Relevant to Groundwater

Sentinel-1 provides consistent, high-resolution surface backscatter data that can be used to derive soil moisture estimates, particularly in low-vegetation or seasonally bare areas. More importantly for the Indo-Pacific region, Sentinel-1 supports InSAR time-series analysis to detect land subsidence or uplift—a key proxy for groundwater extraction and aquifer compaction. Recent studies have also demonstrated its ability to detect soil salinity trends in coastal areas where freshwater lenses are degrading. These applications are particularly relevant for low-lying islands experiencing salinization, subsidence, or land deformation. For more detailed salinity estimates, SAR is often combined with optical sensors (e.g., Sentinel-2) and machine learning methods.

Usefulness for Groundwater Scope

Very Good. Sentinel-1's all-weather imaging capability, high spatial resolution (10 m), and frequent revisit interval (6–12 days) make it highly effective for detecting subtle land deformation caused by groundwater extraction or aquifer compaction—particularly relevant in low-elevation coral atolls and volcanic islands across the Indo-Pacific. It is especially valuable for tracking subsidence in island capitals, ports, and groundwater-dependent urban zones where freshwater lens over-pumping may not be monitored otherwise. Sentinel-1 has also been shown to detect surface changes linked to coastal salinization, and when paired with Sentinel-2, can delineate areas where salinity stress on vegetation overlaps with subsidence hotspots. Because of its free and open data policy, Sentinel-1 is highly suitable for long-term, island-scale deformation

monitoring without the cost constraints associated with commercial SAR platforms, making it one of the most practical active sensors for groundwater risk assessments in the region.

2.2 PALSAR (JAXA)

Technical Overview

PALSAR and its successors (ALOS/PALSAR-1 and ALOS-2/PALSAR-2) are L-band Synthetic Aperture Radar (SAR) systems developed by the Japan Aerospace Exploration Agency (JAXA). They operate at ~10–30 m resolution, depending on acquisition mode, with repeat cycles of 14 to 46 days (Figure 4). L-band SAR penetrates vegetation more effectively than C-band, making it suitable for soil surface analysis in densely vegetated regions. Data is available via JAXA and ASF DAAC, though access may be restricted or cost-covered depending on region and product level.

Key Variables Relevant to Groundwater

PALSAR is primarily used for soil moisture retrieval in vegetated environments, including tropical islands. Its L-band backscatter is sensitive to changes in surface water content, which can indicate freshwater lens dynamics, salinization, or seasonal recharge. PALSAR has also been used to map land subsidence and soil salinity, particularly when combined with ground-truth or optical data. Its deeper penetration makes it complementary to Sentinel-1 for identifying subsurface conditions in areas with persistent vegetation cover.

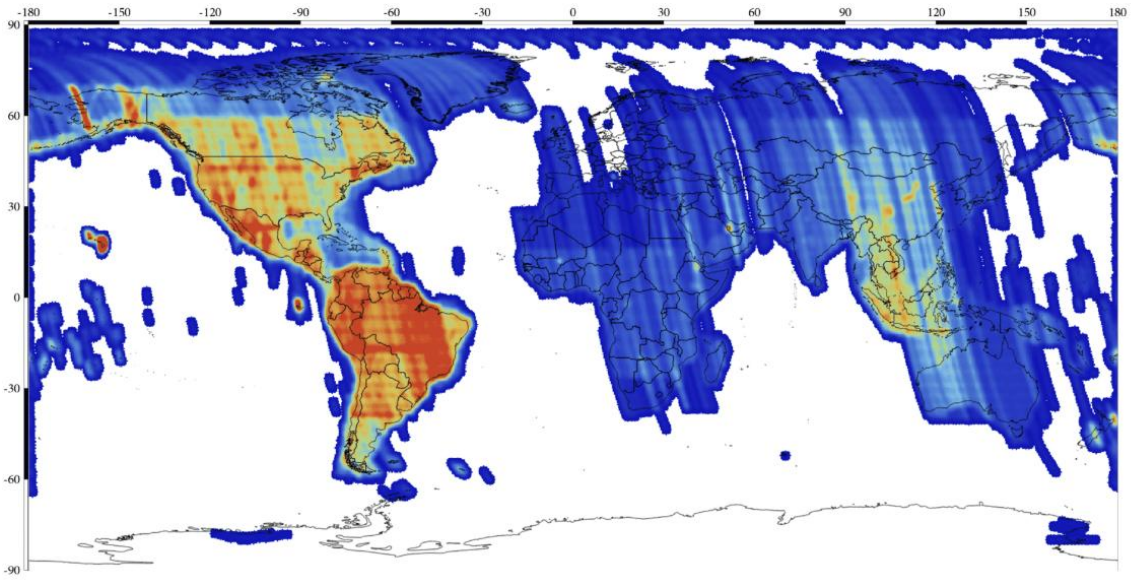


Figure 4: ALOS PALSAR L1.5 Fine Beam Dual Polarization (FBD) Coverage Map.
Source: https://www.earthdata.nasa.gov/

Usefulness for Groundwater Scope

Good. PALSAR provides unique L-band sensitivity to soil moisture and salinity in vegetated zones, which is particularly relevant for low-lying forested islands in the Indo-Pacific. It complements Sentinel-1 for subsidence and salinity mapping but is limited by coarser revisit, data availability, and inconsistent free access. Best suited for targeted analyses in high-priority islands where vegetation masks surface changes from other sensors.

2.3 GRACE / GRACE-FO (NASA/DLR)

Technical Overview

GRACE (2002–2017) and its successor GRACE-FO (launched 2018) are joint missions by NASA and the German Aerospace Center (DLR) that measure variations in Earth's gravity field to estimate changes in total terrestrial water storage. The effective spatial resolution is ~300 km, with monthly observations. Data is freely available through NASA's Jet Propulsion Laboratory and other Earth science data portals.

Key Variables Relevant to Groundwater

GRACE detects large-scale groundwater storage anomalies, integrating contributions from surface water, soil moisture, and aquifers. It has been used to identify groundwater depletion trends, particularly in continental regions and large island systems. In the context of small islands, GRACE is too coarse to resolve individual aquifers but can support regional hydroclimatic assessments, such as groundwater stress in archipelagos, or responses to ENSO-driven droughts.

Usefulness for Groundwater Scope

Limited. GRACE provides valuable insights into regional-scale groundwater trends, but its ~300 km resolution is far too coarse for island-scale freshwater lens assessment. It is best used as contextual data for understanding large-scale groundwater variability, climate–water interactions, or framing transboundary or multi-island resource trends in the Indo-Pacific region. It is not suitable for operational monitoring of individual islands or atolls.

2.4 SWOT (NASA/CNES)

Technical Overview

The Surface Water and Ocean Topography (SWOT) mission, launched in December 2022, is a joint NASA–CNES mission designed to measure surface water extent and elevation at global scale. SWOT uses Ka-band radar interferometry to produce water surface height measurements with a spatial resolution of ~50–100 m and a revisit time of 21 days. Data is freely available from NASA's PO.DAAC portal.

Key Variables Relevant to Groundwater

SWOT measures surface water level and extent in rivers, lakes, and coastal zones, offering potential insights into surface–groundwater interactions, especially in large freshwater bodies where aquifer recharge or discharge occurs. In low-lying island settings, SWOT may detect seasonal fluctuations in lagoon levels or surface inundation events linked to groundwater lens collapse or over-extraction, though only when the features are large and open enough to be resolved by its footprint.

Usefulness for Groundwater Scope

Limited. SWOT's spatial resolution is not sufficient to resolve most freshwater lenses or small inland water bodies common in the Indo-Pacific's small islands. However, it may support regional or archipelagic-scale assessments of coastal hydrology, surface inundation, or oceanic pressure on low-lying aquifers, particularly when paired with sea-level, tidal, and precipitation data. Its greatest value lies in its potential to inform climate and hydrologic context, not direct groundwater monitoring.

2.5 Airborne Electromagnetic Methods (AEM)

Technical Overview

AEM surveys use low-frequency electromagnetic fields emitted from aircraft to measure the electrical conductivity of subsurface materials, which correlates strongly with salinity and moisture content (Figure 5). Typical depth penetration ranges from 30–300 meters, with horizontal resolution of 10–50 meters, depending on system configuration and flight altitude. Surveys are conducted on demand, often with helicopter or fixed-wing systems. Data acquisition is expensive, with costs exceeding $500–$1,500 per km², and campaigns require substantial logistical planning.

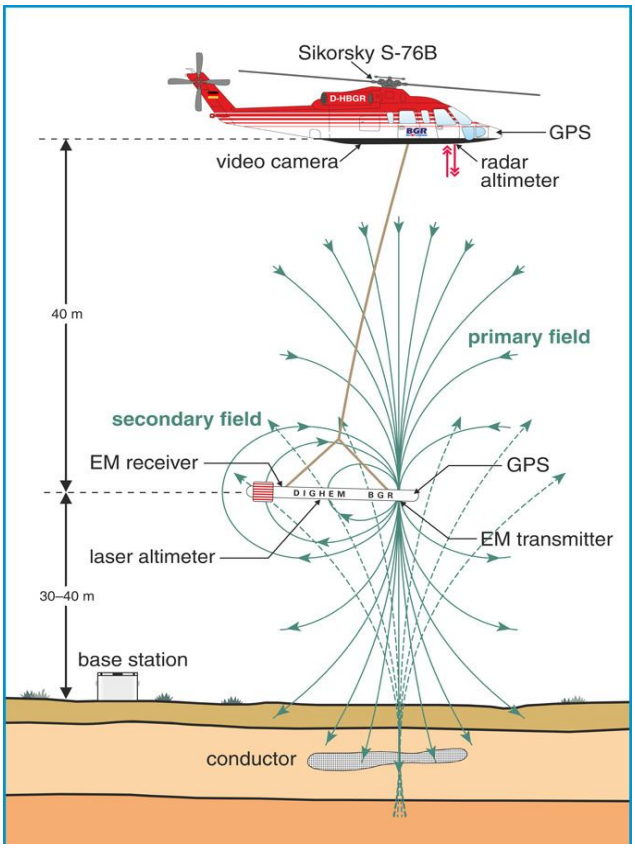


Figure 5: Airborne electromagnetics measuring the conductivity of the shallow subsurface from the air.

Key Variables Relevant to Groundwater

AEM is uniquely capable of directly mapping freshwater–saltwater interfaces, identifying freshwater lens thickness, and detecting salinization zones in coastal aquifers. It is the most reliable remote sensing method for three-dimensional mapping of groundwater salinity on small islands, especially where wells are sparse or inaccessible. AEM has been used to assess lens vulnerability and recharge potential in Pacific islands like Tarawa and Tonga, making it one of the few technologies to generate high-resolution, spatially explicit salinity profiles across entire atolls.

Usefulness for Groundwater Scope

Limited. While AEM provides unmatched accuracy and depth for characterizing freshwater lens extent and salinity, it is cost-prohibitive for regional monitoring and not scalable without significant investment. It is best used for baseline assessments, critical groundwater mapping, or model calibration in priority areas. In the Indo-Pacific, AEM has proven transformative in select applications but remains inaccessible for routine use due to its high costs and operational complexity.

2.6 UAV-Based LiDAR

Technical Overview

Unmanned Aerial Vehicles (UAVs) equipped with Light Detection and Ranging (LiDAR) sensors generate sub-meter resolution 3D point clouds for detailed mapping of terrain, vegetation, and surface structures (Figure 6). UAV-LiDAR systems can achieve vertical accuracies <10 cm and are typically deployed for site-specific surveys, covering small areas (<100 km²) per flight. Data acquisition is extremely costly (>$1,500 per km²), and mission planning requires regulatory and technical capacity.

Key Variables Relevant to Groundwater

UAV-LiDAR is used to produce high-resolution Digital Elevation Models (DEMs) that are essential for mapping groundwater recharge zones, modeling lens geometry, and understanding surface-subsurface flowpaths on small islands. On low-relief atolls, small elevation changes (10–30 cm) can significantly influence groundwater lens shape, salinity intrusion pathways, and flood recharge dynamics. LiDAR is also used to detect coastal erosion, storm overwash, and landform shifts that affect aquifer recharge and vulnerability.

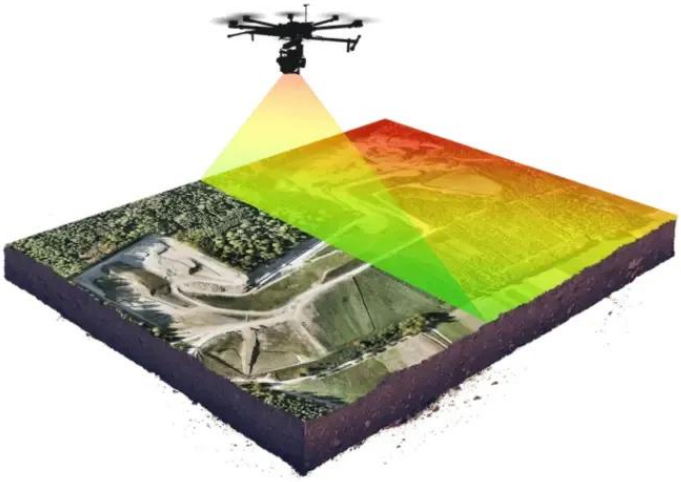


Figure 6: Drone with a LIDAR scanner that shoots millions of laser light pulses to the ground below its flight path.
Source: https://wingtra.com/

Usefulness for Groundwater Scope

Limited. UAV-LiDAR provides the highest-resolution topographic data available, which is critical for lens modeling, recharge delineation, and vulnerability assessments on flat islands. However, the high cost, limited spatial coverage, and need for specialized expertise limit its use to site-specific investigations or pilot-scale mapping efforts. It is best applied in baseline terrain mapping to support hydrologic and salinity modeling in high-priority locations.

Table 2: Primary data from active-sensor remote sensing

Satellite / Mission	Key Variables	Resolution	Usefulness for Small Islands	Reference Example
PALSAR (JAXA)	Soil moisture, deformation	~10–30 m / Varies	Good: Complementary to Sentinel-1	Mostly used for soil salinity
Sentinel-1 (ESA)	Soil moisture, land deformation	10 m / 6–12 days	Very good: All-weather, vegetation-penetrating	Ma et al. 2023. Land Subsidence Assessment of an Archipelago Based on InSAR Time Series Analysis. https://doi.org/10.3390/w15030465 Polcari *et al.* 2024. Monitoring of Small Islands Belonging to the Aeolian Archipelago by MT-InSAR Data. https://doi.org/10.1007/s00024-024-03568-z Hoa, et al. 2019. Soil Salinity Mapping Using SAR Sentinel-1. https://doi.org/10.3390/rs11020128 Hihi et al. 2023. Soil Salinity Monitoring via SAR Data, Sentinel-2 Imagery, and Machine Learning Algorithms in Kerkennah Archipelago. https://doi.org/10.3390/atmos14101514
GRACE / GRACE-FO (NASA/DLR)	Total water storage	~300 km / Monthly	Limited: Too coarse for island-scale use. Useful for synoptic regional trends	Huang et al. 2019. Detect groundwater storage in an island watershed https://doi.org/10.5194/egusphere-egu2020-1827 Gou and Soja, 2024. Global high-resolution total water storage anomalies. https://doi.org/10.1038/s44221-024-00194-w
SWOT (NASA/CNES)	Surface water extent/height	~50–100 m / 21 days	Limited: Low resolution. Useful for synoptic regional trends	launched in December 2022 https://swot.jpl.nasa.gov/news/104/swot-measures-tuvalu-sea-level/?utm_source=chatgpt.com
Airborne Electromagnetic Methods (AEM)	Freshwater lens mapping, salinity interface	10–50 m / on demand	Limited: High-resolution lens data, but costly	Knight, R., et al. (2006) – "Mapping Aquifers with Airborne Electromagnetic Methods". Though not specific to the Pacific, this is a foundational study demonstrating the utility of AEM for aquifer characterization in coastal environments. Kennedy et al. (2022). AEM surveys reveal salinization risk in freshwater lenses of Tarawa and Tonga. Hydrogeophysics Journal, 31(3).
UAVs with LiDAR	Topography, DEMs, 3D representation	<1 m / task-specific	Limited: High-resolution but extremely costly	García-López et al 2023 "UAV-borne LiDAR revolutionizing groundwater level mapping".

3: Spectral Indices for Detecting Groundwater Stress

3.1. Spectral Indices as Proxies for Groundwater Vulnerability

A recent Nature study by Rohde et al. (2024) mapped groundwater-dependent ecosystems (GDEs) globally, highlighting their ecological and hydrologic importance in coastal and island systems. This reinforces the relevance of spectral indices for tracking groundwater availability, salinization, and freshwater lens vulnerability—particularly in remote island settings such as those across the Indo-Pacific region, where in situ data are sparse or nonexistent.

3.2. Core Indices for Vegetation and Moisture Stress

Among the indices evaluated in Table 3, the Normalized Difference Vegetation Index (NDVI) stands out as a highly useful tool for detecting vegetation stress associated with freshwater lens depletion and salinity intrusion. On small islands, where shallow-rooted vegetation depends heavily on groundwater, NDVI anomalies can serve as an early-warning indicator of declining groundwater quality or quantity. Similarly, the Normalized Difference Moisture Index (NDMI) is exceptionally relevant, as it captures variations in vegetation moisture content and has been widely used to assess drought-related stress in groundwater-dependent vegetation. NDMI is particularly sensitive to subsurface moisture deficits and is well-suited for detecting spatial patterns of lens contraction or saltwater upcoming beneath coastal or atoll environments.

3.3. Supplementary Indices for Salinity and Water Detection

Other indices offer more limited but still context-specific utility. The Modified Normalized Difference Water Index (MNDWI), which substitutes shortwave infrared (SWIR) for near-infrared (NIR), can be useful in coastal or built-up areas for distinguishing saline surface water—potentially associated with groundwater discharge or contamination—though its relationship to subsurface processes remains indirect. The original NDWI primarily detects surface water presence and is not inherently tied to groundwater dynamics, though it may help flag lens collapse in extreme cases where surface ponding occurs. Lastly, the Soil-Adjusted Vegetation Index (SAVI) is designed for use in sparsely vegetated or bare-soil conditions. While less useful in humid tropical island contexts, it may be applicable in dry atolls or post-disturbance settings where vegetation cover is limited and shallow groundwater dynamics dominate.

Table 3: Spectral indices and band ratios relevant to groundwater, water, salinity, and moisture studies

Index / Ratio	Formula / Bands	Primary Applications	Example Studies
NDVI (Normalized Difference Vegetation Index)	(NIR - Red) / (NIR + Red)	Vegetation health; indirect groundwater proxy	Parizi et al., 2020 (Sci Rep)
NDWI (Normalized Difference Water Index)	(Green - NIR) / (Green + NIR)	Surface water detection	McFeeters, 1996 (IJRS)
MNDWI (Modified NDWI)	(Green - SWIR) / (Green + SWIR)	Urban water detection	Xu, 2006 (PE&RS)
NDMI (Normalized Difference Moisture Index)	(NIR - SWIR) / (NIR + SWIR)	Vegetation moisture, drought stress	USGS (landsat.usgs.gov)
SAVI (Soil-Adjusted Vegetation Index)	((NIR - Red) / (NIR + Red + L)) * (1 + L)	Vegetation monitoring on bare soils	Huete, 1988 (RS Env)
NDSSI (Normalized Difference Salinity Index)	(SWIR - NIR) / (SWIR + NIR)	Soil salinity estimation	Elnaggar & Noller, 2010 (Geomorphology)
SI1 (Salinity Index 1)	Red / NIR	Bare soil salinity mapping	Allbed et al., 2014 (Geoderma)
TIR Band Ratios	Thermal Band 10 / Band 11	Groundwater discharge detection	Cardenas et al., 2017 (J Hydrol)
NSMI (Normalized Soil Moisture Index)	(SWIR - Red) / (SWIR + Red)	Soil moisture estimation	Liu et al., 2021 (Remote Sens)
WI (Water Index)	NIR / Green	Plant water stress, irrigation	Peñuelas et al., 1993
WRI (Water Ratio Index)	(Green + Red) / (NIR + SWIR)	Surface water discrimination	Shen & Li, 2010
NDTI (Normalized Difference Turbidity Index)	(Red - Green) / (Red + Green)	Water turbidity, sediment	Lacaux et al., 2007
AWEI (Automated Water Extraction Index)	Weighted combination of Green, NIR, SWIR	Water body extraction in shadowed terrain	Feyisa et al., 2014 (RS Letters)
NDII (Normalized Difference Infrared Index)	(NIR - SWIR) / (NIR + SWIR)	Vegetation moisture stress	Hardisky et al., 1983
SWI (Soil Water Index)	(NIR - SWIR) / (NIR + SWIR)	Soil moisture monitoring	Wagner et al., 1999
LSWI (Land Surface Water Index)	(NIR - SWIR) / (NIR + SWIR)	Flood/wetland water detection	Xiao et al., 2005
GNDVI (Green NDVI)	(NIR - Green) / (NIR + Green)	Vegetation photosynthetic activity	Gitelson et al., 1996
NDSI (Normalized Difference Snow Index)	(Green - SWIR) / (Green + SWIR)	Snowmelt and recharge monitoring	Hall et al., 2002 (MODIS Snow Cover)

Overall, NDVI and NDMI emerge as the most applicable indices for monitoring groundwater potential, quality, and salinity impacts in small island settings. These indices are strongly recommended for integration into remote sensing workflows for groundwater-related assessments across the Indo-Pacific, with others like MNDWI and SAVI offering supplementary insight under specific conditions. A full list of formulas and application notes is provided in Table 3.

4: Secondary Datasets Supporting Groundwater Assessment

4.1. Why Secondary Data Matter in the Indo-Pacific Context

Groundwater monitoring in the Indo-Pacific region is fundamentally limited by a lack of field infrastructure and sparse in situ observations. Most small islands lack boreholes, piezometers, salinity gauges, or soil moisture monitoring systems. Even where field campaigns exist, their coverage is often highly localized, outdated, or inaccessible for operational use. Remote sensing offers a powerful workaround—but on its own, it cannot fill all the gaps.

Secondary geospatial datasets, especially those built from large-scale observations and models, can play a critical supporting role. These datasets help bridge the spatial and thematic gaps in island-scale analysis by providing essential hydrologic, climatic, geomorphic, and water quality variables. They serve two primary functions: (1) providing regional or global context for interpreting remote sensing anomalies, and (2) offering model inputs and boundary conditions for estimating freshwater lens thickness, salinity vulnerability, and recharge variability.

However, their usefulness is often constrained by spatial mismatch. Many of these datasets were developed for continental or large-basin applications and have native resolutions ranging from 1 km to 50 km or more—orders of magnitude larger than the land area of typical Indo-Pacific atolls. As such, they require careful adaptation, downscaling, or integration with higher-resolution datasets (e.g., from Sentinel-2 or PlanetScope) to produce actionable island-level insights. Despite these limitations, select datasets provide foundational value—especially when combined with physically based lens models, spectral indices, and targeted remote sensing inputs.

4.2. Critical Datasets for Calibration, Terrain, Climate, and Water Quality

Among all secondary data sources, the Geoscience Australia Island Groundwater Dataset is arguably the most valuable for calibration and validation. It provides in situ records of freshwater lens thickness, recharge rates, aquifer vulnerability, and saltwater intrusion risk for selected Pacific islands. These empirical observations allow researchers to train machine learning models, validate spectral index outputs (e.g., NDMI anomalies vs. salinity stress), and refine groundwater lens modeling. Though its spatial coverage is limited, this dataset offers a rare opportunity to ground RS workflows in field-based reality.

For physical model initialization, high-resolution terrain and island morphology data are essential. The Global Island Explorer (GIE) provides accurate island boundaries, widths, and

elevation profiles—variables that directly influence freshwater lens thickness and shape. Island width, in particular, is one of the strongest predictors of lens volume. When combined with GEOMORPHO90, a global 90-meter landform classification product, GIE supports delineation of recharge zones, slope gradients, and hydrologic catchments necessary for modeling infiltration and saltwater intrusion risk. These datasets also enable rule-based island type classification (e.g., coral atoll vs. volcanic high island) for parameterizing model assumptions.

Understanding recharge potential requires datasets that characterize soil moisture and precipitation patterns. SMAP and ASCAT provide daily measurements of surface and root-zone soil moisture at coarse resolutions (9–40 km), which can be useful when downscaled or fused with Sentinel-1 SAR or NDMI data. Global-soil-salinity offers modeled estimates of surface salinity over time, which can reflect capillary salt rise from underlying saline aquifers—especially in agricultural or exposed coastal areas. Although temporally sparse (available for only a few years), this dataset offers a proxy for long-term salinization pressure in lens-dependent landscapes.

To assess ocean-side salinity drivers and freshwater lens pressure, the Global-water-salinity dataset provides 9 km surface salinity estimates derived from OSCAR-modeled data. While too coarse for island-scale use, it helps frame oceanic salinity conditions that may influence aquifer vulnerability—particularly in atolls with porous substrates or thin barriers. Similarly, the DynQual dataset simulates surface water quality parameters (e.g., total dissolved solids, temperature, biological oxygen demand) at ~10 km resolution. These parameters are not direct groundwater indicators but can help identify marine-coastal water quality shifts that may correspond with groundwater discharge, especially when cross-referenced with thermal or chlorophyll imagery.

Lastly, the Global Surface Water and Groundwater Salinity Samples dataset compiles over 16 million empirical observations of salinity from more than 200,000 locations globally. Although coverage is uneven and spatially sparse in some Pacific nations, this database provides invaluable reference points for model calibration and regional salinity trend analysis. In the absence of island-specific monitoring, it remains one of the few accessible sources of real-world salinity data.

4.3. Coarse-Scale Models and Regional Groundwater Context

While most of the datasets described above offer high spatial specificity or empirical precision, several global models provide important regional context—even if they cannot resolve island-scale aquifer dynamics directly.

The GLOBGM (Global Groundwater Model) provides physically based simulations of groundwater heads, recharge, and discharge at ~1 km resolution. Although it was not developed for island settings and lacks calibration for most tropical coastal zones, GLOBGM remains useful for framing comparative analyses across archipelagos, simulating regional recharge scenarios, or benchmarking lens modeling outcomes against broader groundwater flow trends. Its outputs can also inform sensitivity analyses when high-resolution local parameters are unavailable.

The GRACE / GRACE-FO missions, which detect terrestrial water storage changes via satellite gravimetry, represent one of the most powerful tools for understanding basin- and region-wide water availability trends. While the native resolution (~300 km) is far too coarse for individual islands, recent advances in statistical downscaling—such as the open-source GRACE Downscaling Toolkit—enable its use in regional anomaly detection and hydrologic baselining. GRACE is especially valuable for understanding long-term aquifer trends under ENSO cycles, persistent drought, or multi-year recharge deficits across groups of islands.

Both GLOBGM and GRACE are best understood as contextual layers rather than operational monitoring tools. They are essential for identifying large-scale patterns, framing climate-driven groundwater anomalies, and guiding where more detailed analysis or fieldwork may be warranted. When paired with high-resolution RS and empirical data, they help transform isolated observations into system-level understanding.

4.4. Summary of Secondary Datasets

Table 4 consolidates the key secondary datasets evaluated in this chapter, highlighting their main variables, spatial resolution, relevance for small island groundwater monitoring, and primary references. This table serves as a reference point for selecting complementary data inputs when designing remote sensing workflows or freshwater lens models across the Indo-Pacific.

Table 4: Secondary Data & Databases for Groundwater Assessment

Database	Key variables	Resolution	Usefulness for small islands	Reference
Geoscience Australia – Island Groundwater Dataset	Groundwater Recharge, Aquifer Vulnerability, Saltwater Intrusion, Freshwater Lens, Climate Change Impacts, Sea-Level Rise, Drought Susceptibility, Island Type, Hydrogeology	Site-specific	Excellent: Foundational data for small island hydrogeology. Can be used as training to model and predict groundwater related variables across the INCOPACOM	Dixon-Jain et al. 2014. Pacific Island Groundwater and Future Climates: First-Pass Regional Vulnerability Assessment. https://doi.org/10.11636/Record.2014.043
Global Groundwater-Dependent Ecosystems (GDEs)	Groundwater Table Depth, Ecosystem Type, Vegetation Indices, Soil Moisture Content, Precipitation Rates	30m	Excellent: spatially explicit insight into where ecosystems rely on groundwater—supporting the identification of vulnerable freshwater lenses and conservation priorities on small islands in the Indo-Pacific region	Rohde et al. 2024. Groundwater-dependent ecosystem map exposes global dryland protection needs. Nature 632, 101–107.https://doi.org/10.1038/s41586-024-07702-8
SMAP / ASCAT	Surface & root-zone soil moisture	9–40 km / daily	Limited: Requires downscaling or fusion with field data	Entekhabi et al. 2010. The Soil Moisture Active Passive (SMAP) Mission. https://doi.org/10.1109/JPROC.2010.2043918
GEOMORPHO90-GEOMORPHOLOGICAL-FORMS	Landform classification, slope, elevation	90 m	Very Good: Supports groundwater modeling via terrain analysis	
GLOBAL-WATER-SALINITY	Surface water salinity	~9 km 1992–2024	Limited: Coarse, useful only for regional patterns. Sea surface salinity can help assess ocean-driven pressures on freshwater lenses in small islands and model saltwater intrusion risk, seasonal ocean variability, and groundwater vulnerability in coastal atolls	Cummings and Smedstad. 2013. Variational Data Assimilation for the Global Ocean. Data Assimilation for Atmospheric, Oceanic and Hydrologic Applications vol II, chapter 13, 303-343.

GLOBAL-SOIL-SALINITY	Soil Salinity Levels	~1 km Temporal: Data available for 1986, 1992, 2000, 2002, 2005, 2009, 2016.	Good: soil salinity serves as a proxy for groundwater quality and presence, especially in small islands where freshwater lenses are vulnerable to saltwater intrusion.	Ivushkin et al. 2019. Global mapping of soil salinity change. https://doi.org/10.1016/j.rse.2019.111260
GLOBGM-GROUNDWATER-MODEL	Groundwater Heads, Water Table Depth, Groundwater Flow, Recharge Rates, Discharge Rates	~1 km	Good: Useful for context and regional trends and for downscaling groundwater availability, understanding the impacts of climate change on freshwater resources	Verkaik et al. 2024. GLOBGM v1.0: A parallel implementation of a 30 arcsec PCR-GLOBWB-MODFLOW global-scale groundwater model. https://doi.org/10.5194/gmd-17-275-2024
DynQual Global Surface Water Quality	Water Temperature (Tw), Total Dissolved Solids (TDS), Biological Oxygen Demand (BOD), Fecal Coliform (FC)	~10 km Temporal: Daily simulations from 1980 to 2019	Limited: Coarse, useful only for regional patterns to model water quality and freshwater vulnerability on small islands	Jones et al. 2023. DynQual v1.0: a high-resolution global surface water quality model. https://doi.org/10.5194/gmd-16-4481-2023
Global Surface water and groundwater salinity measurements	Surface Water Salinity, Groundwater Salinity, Temporal Changes	16.3 million samples, from 45,103 surface water locations and 208,550 groundwater locations around the world. (1980-2019)	Good: Tracks long-term salinity changes in surface and groundwater, critical for small islands with limited freshwater. Helps identify areas at risk of saltwater intrusion	Thorslund et al. 2020. A global salinity dataset of surface water and groundwater measurements from 1980-2019. https://doi.org/10.1594/PANGAEA.913939

5: Coastline and Landmask Datasets for Modeling Freshwater

5.1. The Importance of Accurate Coastlines in Small Island Hydrogeology

In small island environments, especially those across the Indo-Pacific region, freshwater lens dynamics are closely tied to the physical structure of the island—particularly its coastline geometry, land area, and elevation. Even minor inaccuracies in coastline delineation can significantly distort estimates of recharge zones, lens width, and salinization risk. This is because most freshwater lenses are thin, perched on narrow strips of porous substrate, with their boundaries defined by island shape and proximity to the sea. Storm overwash, coastal erosion, or sea-level rise can rapidly shrink lens-supporting areas. Without precise land–water boundaries, modeling efforts risk over- or underestimating the volume, vulnerability, or recharge potential of these lenses. Yet, many global hydrologic datasets still rely on coarse or static landmask products that fail to reflect ongoing shoreline change. For small islands, this is not just a technical limitation—it's a critical blind spot.

5.2. Overview of Key Coastline and Landmask Datasets

Several global coastline datasets have been developed to support hydrologic and land-change modeling. While these vary in spatial resolution and data source, most are **static**—representing coastlines at a single point in time—and therefore do not capture erosion, accretion, flooding, or overwash, all of which are highly relevant to freshwater lens stability in the Indo-Pacific.

Three datasets are especially relevant for modeling freshwater lens boundaries:

- **GLOBAL_SHORELINES** provides vector shoreline features at ~1:250,000 scale. While suitable for broad-scale modeling, it lacks the resolution to detect fine-scale coastline change or small islets and cannot be used for dynamic monitoring.
- **DAYLIGHT LAND-WATER POLYGONS** offer ~30-meter resolution satellite-derived landmask data. This product is better suited for delineating land–water boundaries in recharge models but still represents a static snapshot and does not capture short-term change or seasonal flooding.
- The **Global Island Explorer (GIE)** stands out as the most suitable for small island applications. It combines high-resolution coastline vectors with island-level elevation data, enabling delineation of hydrologic units, recharge zones, and barrier features relevant to lens modeling. GIE has been widely used in island hydrogeology studies to

define freshwater lens width, island typologies (e.g., coral atoll vs. volcanic), and topographic controls on aquifer vulnerability.

Despite their utility, all of these datasets must be considered baselines, not monitoring tools. They are valuable for defining freshwater lens geometry or initializing models but are not capable of capturing ongoing coastal change.

5.3. Toward Dynamic Shoreline Monitoring

While static landmask datasets provide foundational geographic boundaries, they are insufficient for tracking the dynamic coastal processes that drive salinization and aquifer collapse. Storm surge, tidal flooding, and long-term erosion directly impact freshwater lens shape and stability—particularly on flat atolls where small vertical shifts can inundate large portions of the recharge zone.

To capture these changes, static coastline products must be paired with high-resolution optical or radar imagery. For example, Sentinel-2, PlanetScope, or WorldView imagery can be processed to extract shorelines using automated geo-segmentation techniques. Similarly, Synthetic Aperture Radar (SAR) data from Sentinel-1 can be used to monitor shoreline displacement under cloud cover or at night. Such dynamic mapping approaches are essential to assess:

- Land loss and recharge zone shrinkage over time
- Temporary flooding or overwash events after storms
- Long-term erosion trends affecting lens volume
- Shifts in hydraulic connectivity between coastal and interior zones

Without these capabilities, models based on static boundaries risk underestimating salinity exposure and failing to identify islands at the highest risk of aquifer degradation. Table 5 summarizes the key coastline and landmask datasets discussed in this chapter, including their spatial resolution, applications, and limitations for small island groundwater modeling.

Table 5: Ancillary data and coastlines

Database	Key Variables	Resolution	Usefulness for Small Islands
GLOBAL_SHORELINES	Shoreline vectors and features	~1:250,000	Good: Helpful for salinization modeling, barrier mapping
DAYLIGHT-LAND-WATER-POLY	Coastline, ocean/land boundaries	~30 m	Good: Supports shoreline delineation for recharge models
Global Island Explorer (GIE)	Island boundaries, elevation, hydrological delineation	High-resolution	Excellent: Defines modeling boundaries and recharge zones

6: Global Hydrologic Datasets for Groundwater Modeling

6.1. Why Hydrologic Context Matters for Groundwater Lens Modeling

Modeling freshwater lens thickness, recharge potential, and salinization risk on small islands requires more than just groundwater datasets. Hydrologic processes such as surface runoff, ponding, wetland persistence, and catchment routing all play critical roles in governing where and how groundwater is recharged. On low-lying islands, even minor changes in elevation or surface water presence can affect lens stability, especially when storm events, seasonal inundation, or wetland connectivity alter recharge pathways or salinity exposure.

In many cases, these controls are not captured by traditional aquifer datasets. Instead, they must be inferred from global hydrologic products that map surface water dynamics, flow direction, terrain, and environmental attributes. While originally developed for continental or regional-scale hydrologic modeling, several of these datasets offer sufficiently high resolution and time-series depth to support island-scale applications—particularly when used alongside high-resolution remote sensing products and terrain models.

These datasets are especially valuable for baseline characterization of surface hydrology, identifying recharge zones, and setting up physical boundary conditions for lens modeling frameworks. They are not suitable for direct groundwater estimation, but they provide critical scaffolding to support modeling and decision-making where field-based hydrologic data is unavailable.

6.2. Key Datasets for Surface Water, Wetlands, Routing, and Terrain

A number of global datasets provide foundational information about surface water dynamics, wetland extent, and hydrologic flow structure—all of which can support recharge modeling and freshwater lens delineation.

The JRC Global Surface Water dataset provides monthly, 30-meter resolution data on surface water presence and change from 1984 to 2022. This long time series enables detection of changes in recharge zones, collapse of freshwater lenses into surface ponds, or progressive saltwater inundation—especially important in atoll settings where small changes in water table depth or island shape can drastically alter lens structure.

GLCF Global Inland Water, a static Landsat-derived product, offers high-resolution (30 m) mapping of inland water bodies and seasonal wetlands. Though not dynamic, it is useful for identifying surface water features that may serve as groundwater recharge zones or indicators of

shallow lens salinization. Similarly, the Global Surface Water Dynamics dataset adds time-varying insight into water persistence and flood trends, helping model how transient ponding might affect lens recharge.

The GWL_FCS30 Global Wetlands dataset maps wetland categories (e.g., saline marsh, freshwater swamp) at 30-meter resolution on an annual basis. This can support wetland–aquifer connectivity analysis and identify groundwater-dependent ecosystems that are vulnerable to salinity shifts.

For hydrologic routing, MERIT Hydro provides 100-meter resolution flow direction, river networks, and drainage structure derived from a corrected global DEM. On islands with sufficient elevation, MERIT Hydro supports terrain-driven recharge modeling and can help simulate water movement toward or away from lens areas. WWF HydroATLAS offers over 280 hydrologic and environmental attributes at 500-meter resolution, including land cover, soil type, and climate variables. These can be used to classify islands by hydrologic characteristics and inform recharge modeling where high-resolution inputs are lacking.

Together, these datasets provide critical environmental and structural context for groundwater modeling efforts. They help define where recharge occurs, how water moves across the island, and how changes in surface water dynamics may influence lens shape, salinity, or seasonal fluctuation.

6.3. Supplementary Hydrologic Products for Modeling Support

In addition to routing and surface water datasets, a few supplementary products provide supporting data that, while coarse, may still prove useful for framing model inputs or validating hydrologic assumptions.

The GPWv411 Water Area dataset offers 1-kilometer resolution estimates of water area in 5-year intervals from 2000 to 2020. Though too coarse for detailed island work, it can support broader assessments of land loss, inundation trends, or sea-level encroachment—especially when paired with shoreline or landmask datasets described in Chapter 5.

The GLOBathy Global Lakes Bathymetry dataset provides lake depth and morphology at 30-meter resolution. While most Indo-Pacific islands do not contain large freshwater lakes, this dataset may be relevant in volcanic islands with crater lakes or elevated inland water bodies, where bathymetry can influence recharge or salinity intrusion patterns.

While these datasets are limited in spatial resolution or island-specific calibration, they remain valuable for parameter estimation and model initialization. When combined with higher-resolution datasets (e.g., from Sentinel-2 or PlanetScope), and field-calibrated inputs where available, they enable a multi-layered approach to understanding freshwater lens dynamics in data-sparse regions. Table 6 provides an overview of the hydrologic datasets discussed in this chapter, summarizing their key variables, spatial resolution, and relevance for small island groundwater modeling.

Table 6: Global Hydrological and Water-Related Datasets

Database	Key Variables	Resolution	Usefulness for Small Islands	Citation (Author(s), Year & DOI)
GPWv411: Water Area	Water area estimates	1 km / 5-year (2000–2020)	Limited: Coarse-scale estimates, useful for broader patterns	CIESIN (2018), https://doi.org/10.7927/H4Z60M4Z
GLCF: Landsat Global Inland Water	Inland water, snow/ice extent	30 m / Static (2000)	Very Good: High-res water delineation	Feng et al. (2016), https://doi.org/10.1080/17538947.2015.1026420
JRC Global Surface Water	Water occurrence, change, duration	30 m / Monthly (1984–2022)	Excellent: Long-term water variability monitoring	Pekel et al. (2016), https://doi.org/10.1038/nature20584
MERIT Hydro	Flow direction, land/water, river width	100 m / Static (1987–2017)	Good: Useful for hydrological routing	Yamazaki et al. (2019), https://doi.org/10.1029/2019WR024873
WWF HydroATLAS	Hydrology, climate, soils, land cover (281 attributes)	500 m / Static (2000)	Good: Regional context, supports modeling input	Linke et al. (2019), https://doi.org/10.1038/s41597-019-0300-6
GLOBathy Global Lakes Bathymetry	Lake depth, bathymetry	30 m / Static (2022)	Very Good: Useful for island lake-based aquifer modeling	Khazaei et al. (2022), https://doi.org/10.1038/s41597-022-01132-9
Global Surface Water Dynamics	Monthly/annual water presence & dynamics	30 m / Monthly (1999–2021)	Excellent: Tracks hydrological variability at fine scales	Pickens et al. (2020), https://doi.org/10.1016/j.rse.2020.111792
GWL_FCS30: Global Wetlands	Wetland categories (e.g., saline marsh, inland swamp)	30 m / Annual (2000–2022)	Excellent: Supports wetland-aquifer connectivity analysis	Zhang et al. (2023), https://doi.org/10.5194/essd-15-265-2023

7: Implementing a Freshwater Lens Model for Atoll Islands

7.1. Modeling Freshwater Lenses in Data-Scarce Island Settings

The small islands of the Indo-Pacific region face acute challenges in managing their groundwater resources. Shallow freshwater lenses—narrow bodies of freshwater floating atop saline groundwater—are the primary water supply for many atoll and reef islands. These lenses are inherently vulnerable: only a few meters thick in many cases, highly sensitive to over-extraction and drought, and frequently exposed to salinization from sea-level rise, storm surges, and coastal erosion.

Despite their importance, freshwater lenses in the Indo-Pacific remain under-monitored and poorly characterized. The logistical difficulty and high cost of field-based hydrogeological surveys, combined with the sheer number and dispersion of islands, make traditional groundwater mapping infeasible at scale. In this context, a remote sensing–enabled, scalable modeling approach becomes not just useful but essential.

To address this need, this chapter presents an implementation of a physically based freshwater lens model—adapted from the algebraic approach proposed by Bailey et al. (2010)—that estimates lens thickness and volume across small islands using remotely sensed and open-access geospatial inputs. The model was designed to be spatially scalable, empirically grounded, and reproducible across diverse island morphologies.

7.2. Model Framework and Input Parameters

The Bailey et al. model estimates maximum lens thickness and volume based on simple hydrogeologic relationships involving island width, recharge rates, hydraulic conductivity, and other site-specific parameters. Because it is algebraic rather than process-based, the model is computationally lightweight and adaptable to spatial automation.

To tailor the model to Indo-Pacific island conditions, key input variables were derived from remote sensing datasets and global environmental products, as described in earlier chapters. Table 7 summarizes the core parameters and the recommended method for estimating each:

- **Maximum island width** is calculated using the Global Island Explorer (GIE) dataset, supplemented by high-resolution coastline segmentation to extract transects.
- **Elevation** is obtained from SRTM or Copernicus GLO-30 DEMs, depending on availability and resolution needs.

- **Island type** (e.g., coral atoll, volcanic island) is classified using slope, elevation, and geomorphic data.
- **Rainfall** is estimated using CHIRPS and IMERG-GPM data, bias-corrected with any available station records.
- **Recharge rates** are derived as a percentage of rainfall, adjusted by island type, vegetation, and surface permeability—drawing on MODIS evapotranspiration data and land cover maps.
- **Hydraulic conductivity** is assigned based on island substrate type, using values from published studies (e.g., Bailey et al., Gingerich, USGS Pacific groundwater assessments).
- **Thurber Discontinuity Depth** (the depth to the impermeable base layer) is estimated from geological literature and applied as a constant per island type.
- **Drought sensitivity** is incorporated via long-term Standardized Precipitation Index (SPI-12) values, derived from CHIRPS anomalies and ENSO phase overlays.

Each variable is mapped spatially, and the model is run across the island footprint using a rule-based classification to assign default or estimated values where data are sparse. The result is an island-by-island map of estimated freshwater lens thickness, total lens volume, and sensitivity to drought or sea-level pressure.

7.3. Elevation, Width, and Reef Influence: Topographic Controls

Topography plays an outsized role in freshwater lens dynamics. On flat islands, even small changes in elevation—on the order of 10 to 30 cm—can dramatically affect aquifer thickness, recharge potential, and vulnerability to saltwater intrusion. Using DEMs such as SRTM or GLO-30, maximum elevation is extracted and paired with island width measurements from GIE to constrain the spatial extent of potential lens zones. In low-relief systems, additional validation is performed using bathymetric data from GEBCO 2023, ensuring consistency between island and reef profiles. The presence of a surrounding reef flat also influences hydraulic behavior and protection against overwash. Reef flat width and slope are mapped using GEBCO bathymetry and used to flag islands with high exposure to storm surge or limited offshore buffering.

7.4. Climate Inputs and Recharge Estimation

Current rainfall inputs are derived from long-term CHIRPS or GPM-IMERG climatologies, bias-corrected where station data are available. Projected rainfall (2050–2085) is taken from CMIP6 model ensembles and statistically downscaled using quantile mapping against CHIRPS baselines. Seasonal variability is captured using monthly climatologies. Recharge rates are estimated as a percentage of total rainfall, typically between 30% and 60%, depending on island type, land cover, and soil permeability. MODIS evapotranspiration data helps validate recharge assumptions and identify seasonal peak recharge periods. Drought effects are integrated using SPI-12 anomalies, with each island classified into low, medium, or high drought sensitivity based on historical variability and ENSO-linked drought cycles.

7.5. Model Outputs and Interpretation

The model outputs a maximum lens thickness (Zmax) for each island, which is then used to compute total lens volume using the spatial extent of the recharge-supporting area and a representative porosity value. Porosity is assigned based on island substrate—e.g., 0.25 for volcanic rock, 0.35 for reef sand.

Outputs include:

- Estimated maximum freshwater lens thickness (in meters)
- Total freshwater volume (in cubic meters)
- Sensitivity classification (e.g., drought-exposed, reef-protected, elevation-constrained)

These products enable a first-pass vulnerability assessment across a wide array of islands, helping to flag priority sites for further study, model refinement, or intervention. They can also be used to benchmark or validate higher-resolution field or airborne data (e.g., from AEM surveys or UAV-LiDAR).

7.6. Benefits, Limitations, and Use Cases

The main strength of this model lies in its scalability and reproducibility. Because it relies exclusively on remote sensing and global datasets, it can be applied to hundreds of islands with minimal field data. It offers a fast, interpretable, and cost-effective means of assessing groundwater availability in places where no other method is feasible.

However, the model has important limitations:

- It assumes idealized aquifer geometry and homogeneous conditions.

- It does not account for well drawdown, urban abstraction, or site-specific pumping data.
- It cannot resolve short-term fluctuations or tidal influences.
- It is sensitive to uncertainties in recharge and porosity values.

Despite these limitations, the model provides a critical baseline for understanding freshwater availability in at-risk island systems. When paired with remote sensing–based monitoring (e.g., NDMI anomalies, salinity trends, or coastal change), it forms the foundation of a proactive groundwater risk framework for the Indo-Pacific.

Table 7: Model Input Parameters and Proposed Estimation Methods for Indo-Pacific Atoll Islands

Variable	Recommended Estimation Method for Indo-Pacific
Maximum Width (km)	Use high-resolution coastline vectors (e.g., DAYLIGHT, Global Island Explorer) combined with morphological analysis to extract maximum island width. Supplement with object-based image segmentation from high-res imagery for shape-sensitive cases.
Maximum Elevation (m)	Use global elevation products such as SRTM (30 m) or Copernicus GLO-30 DEM for consistent coverage and improved vertical accuracy (~2–5 m). For low-lying atolls, validate with GEBCO 2023 nearshore bathymetry where terrain blends into coastal flats. Where higher resolution is required (e.g., for lens edge modeling), manually validate with Google Earth elevation profiles. If budget allows, use ICESat-2 ATLAS photon-counting LiDAR (vertical accuracy ±10 cm); integrate UAV LiDAR for critical sites.
Island Type	Classify using a combination of existing global island typologies (e.g., GIE, GADM), coastline morphology, and DEM-derived slope and elevation thresholds. Apply rule-based classification (e.g., coral atoll = low elevation + ring shape) using open-source spatial data and published geomorphic criteria. Where needed, refine using Google Earth visual inspection or manual expert labeling.
Rainfall (Current)	Use CHIRPS or IMERG/GPM at 0.05° daily resolution; supplement with station data and apply bias correction; model recharge using MODIS ET or SMAP.
Rainfall Projections (2050/2085)	Use CMIP6 multi-model ensemble projections for SSP scenarios. Apply regional statistical downscaling methods (e.g., quantile mapping or delta change) to improve spatial resolution over islands. Use 30-year averages for near- and far-future periods.
Hydraulic Conductivity	Apply published values for different island types (e.g., coral atolls, volcanic islands) based on global or regional literature (e.g., Bailey et al., 2010; Gingerich, 2013). Where refinement is needed, use soil/sediment class derived from landform type and geological context (e.g., reef sediments, consolidated limestone). Field calibration via slug tests or grain-size analysis may be possible in pilot sites.
Thurber Discontinuity Depth (m)	Use published average values from geological studies of similar atolls (e.g., 8–25 m depth to the Pleistocene unconformity). Assign a fixed or island-type-specific default value in the

Variable	Recommended Estimation Method for Indo-Pacific
	absence of site-specific seismic or borehole data. Flag as an uncertainty parameter in sensitivity analyses.
Reef Flat Plate Presence	Use GEBCO 2023 bathymetry or other global bathymetric datasets in Google Earth Engine to delineate reef flat zones based on depth thresholds and slope. Identify reef flat presence, width, and proximity to island core using automated or semi-automated spatial classification.
Recharge Rate (% of rainfall)	Estimate as a fixed fraction of rainfall (30–60%) based on island type and land cover, drawing from published studies. Use ranges from literature (e.g., Bailey et al., 2010; Gingerich, 2013), with higher recharge in vegetated, permeable islands and lower in developed or compacted soils. Use MODIS ET and CHIRPS rainfall to validate general patterns where available.
Drought Factor	Apply published drought factors from Bailey et al. (2010) as first-order estimate; Alternatively, use the Standardized Precipitation Index (SPI-12) calculated from CHIRPS or GPM rainfall data to quantify long-term drought severity. Overlay with ENSO phase information to characterize multi-year drought risk. Assign low, medium, or high drought sensitivity classes accordingly.
Freshwater Volume	Estimate volume using the Bailey et al. (2010) algebraic lens thickness model applied across the island's spatial extent. Multiply estimated lens thickness (Zmax) by island area and porosity assumptions to derive approximate volume. Use published porosity values for reef and volcanic substrates.
Seasonal Variation	Estimate lens seasonality using monthly rainfall climatologies from CHIRPS or GPM and vegetation response indices such as NDMI or NDVI (e.g., MODIS, Sentinel-2). Identify peak recharge and drought periods to characterize seasonal lens dynamics. Use as input for sensitivity bands or monthly recharge adjustment.

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