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**Updated methodology for groundwater level trend analysis**

Draft version

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# Introduction

The growing concern about groundwater depletion in many regions of the world, coupled with a chronic lack of information on the status of groundwater, underscore the urgent need for enhanced monitoring and assessment of groundwater resources. Since 2022, the World Meteorological Organization (WMO) has been publishing an annual report on the State of Global Water Resources[[1]](#footnote-1). Starting in 2023, a section on groundwater levels (GWL) has been included in this report, with IGRAC contributing significantly to the 2023 and 2024 editions.

In the framework of this contribution, IGRAC has developed a methodology to calculate two indicators based on groundwater levels (GWL) monitoring data, i.e. ranking and trend analysis. The methodology is based on a review of existing methodologies worldwide and has been “peer-reviewed” by national experts and researchers. A complete description of the methodology can be found in the methodology report[[2]](#footnote-2). For the groundwater chapter of the WMO State of Global Water Resources 2023 report[[3]](#footnote-3) published in 2024, only GWL ranking indicator was used due to the space constraints of report. Additionally, to date, more than 40 countries have shared with us updated GWL monitoring data, which opens for the opportunity to work on the first “global” assessment of GWL trends with in-situ data.

In order to further refine and complement the ranking and trend indicators, as well as to demonstrate the value of using different indicators to understand changes in groundwater systems, IGRAC proposes an updated methodology in this report. This updated approach builds on the previously peer-reviewed methodology and introduces two key updates, i.e. a normalized Sen's Slope to quantify the magnitude of GWL changes, and hydrograph analysis to better understand the temporal changes in groundwater units.

The main objective of this project is to achieve a more accurate, reliable and harmonized assessment of quantitative groundwater status worldwide, with a higher resolution than those currently offered by global models. This will allow to demonstrate the value of in-situ data in understanding the status of groundwater resources and the underlying drivers of observed changes, therefore motivating countries to monitor groundwater by recognizing the value of information produced for informed decision making.

# Description of the methodology

## Data selection

The data selection methodology follows the approach outlined in the previous peer-reviewed methodology report. The consistency of GWL monitoring data is essential for time series analysis. However, groundwater monitoring practices vary between countries, and even within organizations, resulting in differences in monitoring frequency, timing (e.g. wet or dry season) and spatial distribution of stations, etc. It is therefore challenging to define data selection criteria that can be applied worldwide. Strict criteria ensure high data precision but may limit spatial coverage, while looser criteria enhance spatial representation at the expense of reliability. The proposed methodology aims to balance the trade-offs by maximizing usable data while maintaining consistency and representativeness.

A summary of the methodology is described in the sections below.

### Period of record

Trend analysis and ranking are commonly assessed over long-term time series of 20 years or more. However, recognizing that many countries lack 20 years of data, a fallback to 10-year time series is acceptable when necessary.. Using as many years as available of varying lengths is not considered an option because the results would not be comparable.

### Management of suspicious data and outliers

Erroneous data, such as 0 or -9999 values, will be identified and removed using automatic checks and preliminary dataset inspections. Negative values will also be excluded unless explicitly linked to artesian wells, as GWL are expressed as positive depths below the top of the well.

While it is common in time series analysis to remove outliers, an outlier is not inherently erroneous. Defining rules for outlier removal requires a detailed understanding of the hydrogeological system, which is not feasible for a global assessment. Therefore, this methodology does not include specific procedures for outlier removal.

### Data completeness

Time series with at least one measurement per year will be selected, as long as the measurements are taken during the same period each year to avoid inconsistent time series comprising measurements taken during different seasons. Since seasons vary geographically, the methodology relies on calendar months, as illustrated in Figure 1. Each selected time series consists of monthly values, either from single measurements or averages of multiple measurements taken within the month. Time series with one monthly value per year are acceptable, as long as the percentage of missing years does not exceed the data gap threshold (i.e. 80% per default). More details on the data selection process, including a short video, can be found in IGRAC's repository at this link :[**https://unigrac.github.io/Global-Reporting-Groundwater-Levels/**](https://unigrac.github.io/Global-Reporting-Groundwater-Levels/)

A screenshot of a diagram

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Figure – Flow diagram of the data selection methodology

## Analytical methods

### Trend analysis by significance level

The Mann-Kendall test is used to identify the statistical significance in increasing and decreasing patterns in GWL time series at each site. This method has been widely used for assessing trends in hydroclimate and water variables including GWL. The effectiveness of the Mann-Kendall test relies on the important assumption that data are independent (not correlated). The identification of positive serial correlation raises the probability of the Mann-Kendall test detecting a trend, even in the absence of an actual trend. To address this, auto-correlation tests are performed to identify time series with cyclic patterns, in which case the modified Mann-Kendall test (Hamed and Rao, 1998) is used to account for serial correlation.

To improve the effectiveness of the test and identify potential trends worth further investigation, the significance level is set at 0.1 instead of the commonly used 0.05, i.e., when the p-value is <0.1, there is a significant trend, and when the p-value is >0.1, there is no significant trend.

### Trend analysis by magnitude of change

While the Mann-Kendall test allows to identify statistically significant trends, it does not quantify the magnitude of changes in GWL. This can be estimated using Sen's Slope (also known as Theil-Sen Slope) (Sen, 1968; Theil, 1950), which is defined as the median of the set of slopes between all pairs of points. This approach is less sensitive to outliers than linear regression, thus providing a more robust estimate.

However, the unit change in GWL estimated by Sen's slope is not directly comparable across sites, considering variations in storage coefficients under different hydrogeological conditions, i.e., a similar GWL variation in aquifers with low storage coefficients represents much smaller groundwater storage changes than in aquifers with high storage coefficients. To evaluate the relative importance of trends, the magnitude of change in GWL is normalized to the range of the data with the Change-to-Range Index (CRI) (Dudley and Hodgkins, 2013). The CRI is calculated as the overall period-of-record change (Sen's slope × years of record) divided by the interquartile range (IQR[[4]](#footnote-4)) of the observations.

The magnitude of GWL change is classified as below based on CRI:

* Strong rising: CRI > 1
* Moderate rising: 0.5 < CRI < 1
* Weak trend: -0.5 < CRI < 0.5
* Moderate declining: -1 < CRI < -0.5
* Strong declining: CRI < -1

### Hydrograph analysis

Hydrographs are time-series plots that represent variations in groundwater levels (GWL) over time. They are useful tools for understanding groundwater dynamics within a specific analysis unit, such as an aquifer or basin. By visualizing temporal changes in GWL across multiple wells, hydrographs help interpret both long-term trends and short-term fluctuations.

Since absolute groundwater levels vary significantly across different wells, even within the same aquifer, normalization of GWL is applied to remove site-specific biases while preserving relative fluctuations, enabling accurate comparison across wells. Each well's GWL are standardized to their long-term average using the formula (grey lines in Figure 2):

Normalized Level = Observed Level − Average Level

Where:

* Observed Level is the measured GWL at a given time.
* Average Level is the average GWL for each well over the study period

The trend and hydrograph analysis are first conducted at the station level, providing localized insights into GWL changes. For an overall summarized view of GWL changes, the individual hydrographs are aggregated to the analysis unit to obtain an Average Normalized GWL (black line in Figure 2):

Spatial aggregation can be conducted over aquifer units where such delineations are available. In cases where aquifer boundary information is unavailable, aggregation can be performed over river basins or hydrosheds. To gain a broader perspective, these station-level results can also be interpreted to show the percentage of monitoring stations exhibiting critical rise or decline in GWL within the analysis unit. These aggregated insights can be included in reports to inform decision-making at regional and national scales.

A graph showing the growth of water levels

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Figure Example of hydrograph analysis

# References

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1. https://wmo.int/publication-series/state-of-global-water-resources [↑](#footnote-ref-1)
2. https://unigrac.github.io/Global-Reporting-Groundwater-Levels/ [↑](#footnote-ref-2)
3. https://wmo.int/publication-series/state-of-global-water-resources-2023 [↑](#footnote-ref-3)
4. Interquartile Range (IQR) represents the range between the first quartile (Q1, 25% of the data points fall below this value) and the third quartile (Q3, 75% of the data points fall below this value). It reflects the spread of the middle 50% of the dataset, making it less sensitive to outliers than the total range. [↑](#footnote-ref-4)