THE HIDDEN PRESSURE ON ALBANIA'S GROUNDWATER: EVIDENCE FROM ALL RIVER BASINS

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ABSTRACT

This paper presents an integrated assessment of groundwater stress across Albania's major river basin systems Drin–Buna, Mati, Ishëm–Erzen, Shkumbin, Seman, and Vjosa including transboundary waters, using national environmental monitoring data. Groundwater conditions were compared for two five-year reference periods, 2005–2009 and 2020–2024, and assessed using the Integrated Groundwater Stress Assessment (IGSA), which combines normalized reference-period groundwater-level change, variability, drought conditions, recovery capacity, and anthropogenic pressure on a common 0–1 stress scale. Developed by the authors for the Albanian data-limited context, IGSA is used here as an application-oriented, screening-level framework. Rather than introducing a new physical groundwater-balance or groundwater-drought metric, the study evaluates IGSA as a domain-specific, screening-level composite architecture that integrates complementary stress dimensions for basin comparison under heterogeneous monitoring conditions. The framework is made explicit through component definitions, normalization and weighting rules, quantitative robustness tests, and an external benchmark, while the limitations to full historical five-component reconstruction are documented. To our knowledge, this is the first basin-scale application of this integrated architecture in Albania. The results show pronounced spatial heterogeneity. Ishëm–Erzen has the highest integrated stress (IGSA = 0.82), followed by Shkumbin (0.66), while Vjosa shows comparatively lower stress (0.44); Drin–Buna, Mati, and Seman occupy intermediate positions. The strongest stress patterns occur in more urbanized and intensively exploited systems, where groundwater abstraction, wastewater pressures, seasonal demand, and hydroclimatic variability interact. Complementary environmental and water quality evidence including wastewater treatment data available through 2026, surface water and bathing water quality data through 2025, tourism growth through 2025, and climate conditions is used to contextualise these pressures rather than being treated as direct causal inputs to IGSA. The findings support IGSA as a first-order screening and prioritisation framework under data-limited conditions and highlight the need for strengthened groundwater monitoring, improved abstraction control, integrated wastewater management, and basin-scale planning that accounts for hydroclimatic variability and increasing seasonal demand

Keywords: *Transboundary waters; Groundwater stress; Aquifer dynamics, IGSA, Hydroclimatic variability; Environmental assessment; Water quality; Monitoring network; Resource depletion; Albania.*

1. INTRODUCTION

Groundwater represents a critical component of freshwater resources, supporting drinking water supply, agriculture, industry, and ecosystem functions worldwide. In Albania, its strategic importance is particularly pronounced, as groundwater accounts for approximately 93% of the country's potable water supply. Maintaining the quantitative and qualitative status of groundwater resources is therefore essential for national water security, environmental protection, and sustainable socio-economic development (Eftimi et al., 2023).

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Groundwater systems respond to interacting hydrogeological, hydroclimatic, environmental, and anthropogenic pressures, including recharge variability, groundwater abstraction, surface water interactions, urban development, and increasing water demand. These pressures may lead to groundwater level decline, increased variability, reduced recharge, and diminished system resilience, with potential implications for aquatic and terrestrial ecosystems and the wider environment. International groundwater stress assessments have therefore increasingly combined indicators of renewable availability, depletion, water use, and system response (Gleeson et al., 2012; Richey et al., 2015a,b; Herbert & Döll, 2019). In Albania, groundwater conditions vary substantially among river basins because of differences in aquifer characteristics, recharge mechanisms, climatic conditions, population distribution, and intensity of water use. Several of these systems, including Drin–Buna and Vjosa, also have a transboundary dimension, making basin-scale assessment relevant to coordinated water resource and environmental management. These differences, together with increasing urban, seasonal, and environmental pressures, make basin-scale comparison important for identifying systems experiencing elevated groundwater stress.

Existing groundwater stress indicators range from groundwater footprint and renewable-stress approaches to groundwater-drought, resilience, and composite-index assessments. Their application depends on appropriate indicator selection, spatial scale, data availability, and methodological transparency (Akbar et al., 2022). In Albania, the limited continuity and spatial coverage of groundwater monitoring data create a need for an integrated framework that can synthesize groundwater dynamics with hydroclimatic, environmental, resilience, and anthropogenic dimensions.

To address this need, the authors developed the Integrated Groundwater Stress Assessment (IGSA) as an application-oriented composite framework for basin-scale screening under Albania's heterogeneous and data-limited monitoring conditions. IGSA combines normalized reference-period groundwater-level changes, groundwater variability, drought conditions, recovery capacity, and anthropogenic pressure within a common 0–1 stress scale. Its international methodological contribution is not a claim that any individual component is new; rather, it is the transparent integration of complementary groundwater-state, drought, recovery, and use-versus-recharge dimensions into one auditable comparison architecture designed for heterogeneous national monitoring systems. This positioning follows established principles of normalization, weighting, aggregation, sensitivity analysis, and validation/benchmarking used in composite-indicator methodology (OECD/European Union/EC-JRC, 2008; Greco et al., 2019).

2. STUDY AREA

The study covers six basin systems in Albania: Drin–Buna, Mati, Ishëm–Erzen, Shkumbin, Seman, and Vjosa. These systems represent the groundwater units investigated in this study and encompass a broad range of hydrogeological settings, including alluvial, karstic, and fractured aquifers. Although the current water resources management framework distinguishes the Ishëm and Erzen river basins as separate management units, they are treated jointly here as the Ishëm–Erzen system, consistent with the groundwater monitoring and assessment framework applied in the study.

2.1. Hydrogeological and geographical setting

The study area extends across northern, central, and southern Albania and includes inland and coastal environments. The investigated basin systems (**Fig.1**) encompass mountainous areas, intermountain depressions, river valleys, and coastal plains along the Adriatic and Ionian Seas. Their hydrogeological characteristics vary substantially, from extensive alluvial and karstic systems to smaller and more intensively exploited aquifers in urbanized areas. Two of the investigated systems have a transboundary dimension. The Drin–Buna Basin is part of the wider transboundary Drin River Basin, shared by Albania, Montenegro, Kosovo, and North Macedonia, while the Vjosa Basin is shared by Albania and Greece. These transboundary characteristics add an important dimension to groundwater and water resource management, particularly with respect to monitoring, data exchange, and coordinated basin planning. The associated aquifers are important sources of drinking water, irrigation, and industrial supply and therefore play a central role in Albania’s water resource security (Eftimi et al., 2023; Pano, 2008).

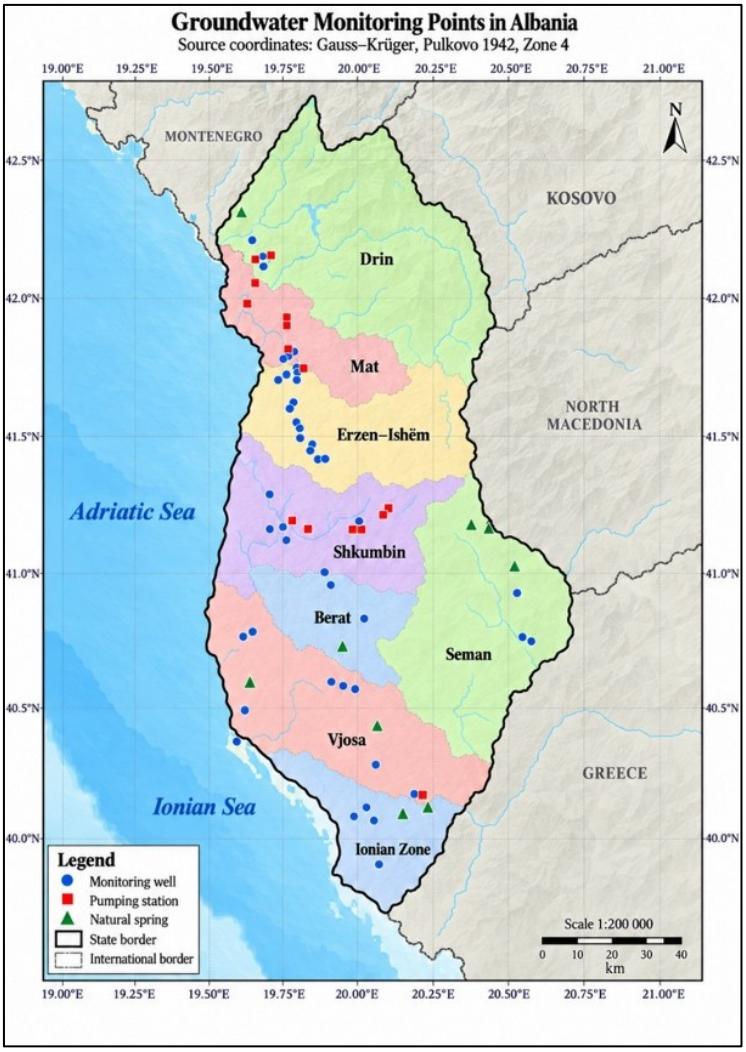


Fig. 1. Study area and hydrodynamic monitoring points in Albania. Background: hydrogeological units; blue points: hydrodynamic monitoring locations. Source: Albanian Geological Survey (AGS) / National Environmental Monitoring Programme; authors' compilation.

Groundwater levels are reported in metres using the signed level convention of the underlying hydrodynamic monitoring records. The available Environmental Status Report does not provide sufficiently explicit evidence of a single common vertical datum applicable to all monitoring stations. Therefore, no additional vertical-datum transformation has been introduced in the present study. Negative groundwater-level values are retained as reported in the source documentation.

The two reference periods were selected to provide a consistent comparison between an earlier monitoring period (2005–2009) and a recent monitoring period (2020–2024). For each basin and period, the reported minimum, mean and maximum groundwater levels were compiled and subsequently subjected to the quality-control procedure described in Section 2.3. The difference between the mean groundwater level of the two periods was then used as the groundwater-level-change component of IGSA.

2.2. Groundwater data quality control and aggregation

A basin-level quality-control procedure was applied to the groundwater-level dataset before calculation of the IGSA components. The QC was performed on the basin-level minimum, mean and

maximum values reported for the two reference periods in the Environmental Status Reports (AKM, 2005–2009; AKM, 2020–2024). The procedure consisted of four steps.

First, the reported groundwater-level statistics were checked for numerical consistency. For groundwater levels expressed using the signed convention of the monitoring records, the expected ordering is:

$$H_{min} \leq H_{mean} \leq H_{max} \quad (1)$$

where H_{min},H_{mean} andH_{max}represent the minimum, mean and maximum groundwater levels, respectively.

Second, the reported values were checked for consistency between the two reference periods and for internal plausibility of the resulting groundwater-level fluctuation. The fluctuation amplitude was calculated as:

$$A = H_{max} - H_{min} \quad (2)$$

where A is the groundwater-level fluctuation amplitude in metres.

Third, the numerical values reported in the source material were retained unchanged. Where the reported minimum and maximum labels were inconsistent with the numerical ordering expected for the signed groundwater-level convention, the values were reassigned to the corresponding minimum and maximum categories without changing the underlying numerical observations. This quality-control step affects the calculated amplitude but does not alter the reported mean groundwater level or the numerical values themselves. Fourth, because the complete original station-level historical observation series and associated metadata for the two reference periods were not available in the source material used for this synthesis, no station-level imputation, interpolation or undocumented correction was undertaken. The analysis therefore remains a basin-level synthesis of reported groundwater-level statistics. As an additional documentary check, the station-level hydrodynamic observations reported in the 2025 Environmental Status Report were examined (AKM, 2025). These records consistently demonstrate the use of signed groundwater-level values and the numerical ordering of minimum and maximum levels. For example, the Ishëm–Erzen monitoring records report minimum values that are more negative than the corresponding maximum values, with amplitudes calculated as the difference between maximum and minimum groundwater levels. Similar reporting is provided for the Drin and Mati monitoring systems (AKM, 2025).

3. DATA AND METHODS

3.1. Analytical framework and data provenance

The Integrated Groundwater Stress Assessment (IGSA), developed by the authors as an application-oriented screening framework for Albania's heterogeneous monitoring conditions, was applied as a composite indicator to compare groundwater stress among the six investigated basin systems: Drin–Buna, Mati, Ishëm–Erzen, Shkumbin, Seman and Vjosa. The framework integrates five dimensions: groundwater-level change, groundwater-level variability, groundwater drought conditions, groundwater recovery capacity, and anthropogenic pressure. Each dimension is transformed to a common 0–1 scale, with higher values representing greater groundwater stress, and the component scores are subsequently aggregated using equal weights. The analytical workflow consists of five sequential steps:

- compilation and quality control of the available groundwater-level data;
- calculation of the raw indicator associated with each IGSA component;
- transformation of each raw indicator to a normalized 0–1 stress score;
- application of equal component weights; and
- calculation of the integrated IGSA score.

The five-dimensional architecture is deliberately modular. Tn represents observed groundwater-state change between reference periods; Vn represents fluctuation behaviour; Dn captures groundwater drought severity; Rn represents the system's ability to recover after stress; and Pn represents pressure from groundwater use relative to natural recharge. The components therefore answer different questions and are not treated as interchangeable substitutes. In contrast to

groundwater footprint, Renewable Groundwater Stress, or Total Groundwater Stress, IGSA does not define stress through a single water-balance ratio, storage-depletion timescale, or footprint. In contrast to SGI, it does not define stress solely through standardized groundwater anomalies. The design objective is instead to retain these complementary perspectives while expressing them on a common stress-oriented scale. This makes IGSA an application-oriented composite framework rather than a new physical law or a universally calibrated sustainability threshold.

Interpretive example. The five components are complementary rather than sequential causal steps. For example, a basin with a reference-period groundwater-level change of −1.2 m has a larger downward shift than a basin with −0.4 m and therefore receives a higher Tn after reverse normalization; a larger fluctuation amplitude increases Vn; more severe negative SGI conditions increase Dn; lower recovery capacity increases stress through (1 − Rn); and a higher abstraction-to-recharge ratio increases Pn. The final IGSA score is the equally weighted aggregation of these stress-oriented component scores. This example is illustrative: because Vn, Dn, Rn and Pn are not fully reconstructable from the archived historical material, it does not assign unavailable component values.

The historical groundwater-level input data were obtained from the National Environmental Monitoring Programme and the Environmental Status Reports of the Albanian National Environmental Agency (AKM) for the two reference periods 2005–2009 and 2020–2024. The available historical material provides basin-level summary statistics rather than the complete original station-level time series. Consequently, the groundwater-level components were reconstructed from the reported basin-level statistics, while no station-level observations were imputed where the original observations were unavailable. The data source, variable, temporal coverage, unit, aggregation level and reproducibility status of each IGSA component are documented in the companion Excel workbook, particularly Sheets 04–09 for provenance, metadata, methods and component reconstruction, and Sheets 10–12 for robustness analysis, external benchmarking and figure data.

The 2025 Environmental Status Report was used only as a documentary quality-control reference for the interpretation of groundwater-level notation and the numerical ordering of minimum and maximum groundwater levels. It was not substituted for the historical observations used in the two reference periods. Because the available historical material contains two common five-year reference periods rather than a continuous annual or monthly station-level series, the groundwater-level component is interpreted as a reference-period groundwater-level change rather than as a statistically tested temporal trend. This distinction is important because a difference between two reference periods does not provide sufficient information for estimating a formal temporal trend or its statistical significance.

3.2. Groundwater-level change component

For basin, the absolute change in the mean groundwater level between the two reference periods was calculated as:

$$\Delta H_{\beta} = \bar{H}_{\beta,2020–2024} − \bar{H}_{\beta,2005–2009} \quad (3)$$

where $\bar{H}_{\beta,2005–2009}$ is the reported mean groundwater level for basin b during the first reference period and $\bar{H}_{\beta,2020–2024}$ is the corresponding value for the second reference period. Under the signed groundwater-level convention used in the source records, a negative ΔH indicates a downward shift in groundwater level, whereas a positive value indicates an upward shift.

The normalized groundwater-level stress component was defined by min–max normalization across the six investigated basin systems:

$$Tn_{\beta} = (\Delta Hmax − \Delta H_{\beta}) / (\Delta Hmax − \Delta Hmin) \quad (4)$$

where ΔHmax and ΔHmin are the maximum and minimum basin-level reference-period changes, respectively. This orientation ensures that a greater downward change produces a higher stress score.

For the present study,is derived from the basin-level mean groundwater levels reported in the Environmental Status Reports. The resulting values are −0.4 m for Drin–Buna, +0.5 m for Mati, −1.2 m for Ishëm–Erzen, −1.1 m for Shkumbin, −0.9 m for Seman and −0.7 m for Vjosa, subject to the final verification of the historical reference-period definition for Shkumbin.

Because the source groundwater levels are signed values, negative numbers represent their position under the source reporting convention and do not denote negative quantities of groundwater. As a supplementary descriptive check, relative reference-period change was expressed as $R\Delta\ (\%) = [\Delta H / |\bar{H}2005–2009|] \times 100$, using the absolute value of the earlier-period mean in the denominator. This avoids the sign reversal that would arise from dividing by a negative signed level. The resulting relative changes are −4.5% (Drin–Buna), +6.8% (Mati), −17.9% (Ishëm–Erzen), −26.2% (Shkumbin), −25.0% (Seman), and −14.9% (Vjosa). This relative measure is reported only as a descriptive diagnostic; the IGSA normalization continues to use the absolute ΔH values so that signed groundwater levels are not converted into misleading ratios.

3.3. Groundwater-level variability component

Groundwater-level variability was represented by the fluctuation amplitude:

$$A_{\beta,p} = Hmax_{,\beta,p} - Hmin_{,\beta,p} \quad (5)$$

where $A_{\beta,p}$ is the groundwater-level fluctuation amplitude for basin b and reference period p, and Hmax and Hmin are the corresponding maximum and minimum groundwater levels.

The amplitude was calculated separately for each basin and reference period. For the integrated comparison, the representative variability measure for each basin was derived from the available reference-period statistics according to the aggregation rule specified in the data table accompanying the analysis. The normalized variability component was calculated as:

$$Vn_{\beta} = (A_{\beta} - Amin) / (Amax - Amin) \quad (6)$$

where A is the documented representative amplitude used for the calculation, and Amin and Amax are the minimum and maximum values across the investigated basin systems.

Higher amplitudes correspond to higher groundwater-stress scores. The amplitude calculation was subjected to the quality-control procedure described in Section 2.3. In particular, the numerical ordering of the minimum and maximum values was checked before calculating amplitude.

3.4. Groundwater drought component

Groundwater drought was represented by the Standardised Groundwater-level Index (SGI), following the standardised groundwater-drought concept of Bloomfield and Marchant (2013). The stress orientation was defined such that increasingly negative groundwater-drought conditions correspond to increasing stress. In a fully reproducible implementation, the SGI component is calculated from the underlying groundwater-level time series for each basin. For a groundwater-level observation series , the SGI is obtained by fitting the distribution of groundwater levels for the selected aggregation period and transforming the cumulative probability to a standard normal variate:

$$SGI_t = \Phi^{-1}[F(H_t)] \quad (7)$$

where $F(H_t)$ is the fitted cumulative probability of the groundwater-level observation H_t and Φ^{-1} is the inverse standard-normal cumulative distribution function. The drought-stress score would then be oriented so that more negative SGI conditions produce higher stress:

$$Dn_{\beta} = (SGImax - SGI_{\beta}) / (SGImax - SGImin) \quad (8)$$

where represents the specified normalization of the basin-level drought indicator to the 0–1 stress scale.

For the present historical synthesis, however, the complete SGI time series and the associated fitting and normalization parameters were not available in the archived source material. Consequently, the Dn values used in the previously reported IGSA results cannot be independently reconstructed from the currently available dataset.

3.5. Groundwater recovery-capacity component

Recovery capacity represents the ability of a groundwater system to recover toward its normal groundwater-level condition following a period of depletion or stress. The component is expressed as a normalized recovery-capacity score , where higher values represent greater recovery capacity and therefore lower stress.

The integrated IGSA formulation uses the inverse of the recovery-capacity score:

$$Rstress,_{\beta} = 1 - Rn_{\beta}. \quad (9)$$

so that lower groundwater recovery capacity contributes positively to the overall stress score.

The operational calculation of requires a defined groundwater recovery metric, its temporal aggregation period, the recovery event identification rule, and the normalization bounds. These parameters must be specified together with the underlying groundwater time series for independent reproduction. The historical source material available for the present synthesis does not contain the underlying recovery-event series or a documented numerical definition of the recovery indicator. Accordingly, an independent recalculation of is not possible from the currently archived dataset.

3.6. Anthropogenic-pressure component

Anthropogenic pressure was represented by the ratio between total groundwater abstraction and natural groundwater recharge:

$$P_{\beta} = Qabs,_{\beta} / R_{\beta} \quad (10)$$

where $Qabs,_{\beta}$ is total groundwater abstraction in basin b and R_{β} is the corresponding natural groundwater recharge, expressed as a volume per unit time, and is the corresponding natural groundwater recharge. A dimensionless ratio greater than one indicates abstraction exceeding the corresponding recharge estimate, whereas lower values indicate a smaller abstraction-to-recharge relationship. The normalized anthropogenic-pressure component was defined as:

$$Pn_{\beta} = (P_{\beta} - Pmin) / (Pmax - Pmin) \quad (11)$$

so that higher abstraction relative to recharge produces a higher stress score.

For reproducibility, the abstraction and recharge datasets must refer to the same basin boundary, temporal reference period and units. The source, year, spatial aggregation and uncertainty of both quantities should therefore be reported together with the resulting ratio. The currently archived study material specifies the abstraction-to-recharge formulation but does not contain the basin-specific abstraction and recharge values, their complete provenance, or the normalization bounds. Consequently, the historical values cannot currently be independently recalculated.

3.7. Normalization and aggregation of the IGSA indicator

Following calculation of the five component indicators, all components are expressed on a common 0–1 stress scale. The normalized components are oriented so that higher values consistently indicate greater groundwater stress. For indicators for which higher raw values represent greater stress, min–max normalization is expressed as:

$$Xn_{\beta} = (X_{\beta} - Xmin) / (Xmax - Xmin) \quad (12)$$

For indicators for which higher raw values represent lower stress, reverse normalization is applied:

$$Xn_{\beta} = (Xmax - X_{\beta}) / (Xmax - Xmin) \quad (13)$$

The normalized components are then aggregated using the weighted additive formulation:

$$IGSA_{\beta} = w_1Tn_{\beta} + w_2Vn_{\beta} + w_3Dn_{\beta} + w_4(1 - Rn_{\beta}) + w_5Pn_{\beta} \quad (14)$$

with:

$$\Sigma_i w_i = 1 \quad (15)$$

In the present study, equal weights were assigned:

$$w_1 = w_2 = w_3 = w_4 = w_5 = 0.20 \quad (16)$$

Thus, each dimension contributes 20% to the final integrated score. The five components have the following stress orientation:

- greater downward groundwater-level change → higher ;
- greater groundwater-level variability → higher ;
- more severe groundwater drought → higher ;
- lower recovery capacity → higher ;
- greater abstraction relative to recharge → higher .

This orientation ensures that an increase in any component consistently corresponds to increasing groundwater stress.

3.8. Stress classification and sensitivity analysis

The resulting IGSA value ranges from 0 to 1. Values approaching zero indicate comparatively low integrated groundwater stress, whereas values approaching one indicate increasingly adverse groundwater conditions. The following classification was applied:

Table 1.

IGSA groundwater stress classification used in the study.

IGSA score	Groundwater stress class
0.0–<0.2	Very low
0.2–<0.4	Low
0.4–<0.6	Moderate
0.6–<0.8	High
0.8–1.0	Very high

The classification thresholds are summarized in **Table 1**. Because complete historical values for Vn, Dn, Rn and Pn are not available, a full five-component uncertainty propagation cannot be reproduced. We therefore performed two quantitative robustness checks on the part of IGSA that can be reconstructed from the archived material. First, reporting/rounding uncertainty was propagated for ΔH and Tn by perturbing each basin-level ΔH by ±0.05 m, corresponding to half the 0.1-m precision of the reported values, and repeating the reverse min–max normalization in Eq. (4) for 200,000 Monte Carlo draws. Second, for the four basins for which a historical composite IGSA score is explicitly documented, the weight assigned to Tn was varied from 0.10 to 0.30 while the remaining four components were redistributed equally and their combined contribution was held at the level implied by the reported composite score. This is a conditional weight-sensitivity test, not a reconstruction of the missing component values. The resulting uncertainty and sensitivity statistics are reported in Section 4.1.8 and **Table 4**. However, because complete component-level inputs are not contained in the archived dataset, a numerical sensitivity analysis of all five components cannot currently be independently reproduced.

For external benchmarking, the four available historical composite IGSA scores were compared with an orthogonal environmental indicator not used as an IGSA input: the mean surface-water quality class for 2018–2025 derived from the national Environmental Status Reports. Higher class numbers indicate poorer surface-water quality. Spearman rank correlation was used because only four basins have documented historical composite IGSA scores. This comparison is treated as an external benchmark of spatial consistency rather than as causal validation, because surface-water quality and groundwater stress are related but distinct processes and the sample size is small.

3.9. Reproducibility and data-availability constraints

Reproducibility was assessed at two levels: algorithmic reproducibility and data reproducibility. The mathematical workflow, normalization direction, weighting scheme and aggregation equation are explicitly defined in this study. However, complete numerical reproduction of the historical IGSA scores requires the original component-level datasets, including the groundwater drought/SGI series, recovery-capacity data, and basin-level abstraction and recharge data, together with their temporal aggregation and normalization bounds. These component-level datasets were not contained in the historical source material available for the present synthesis. Therefore, the IGSA values previously reported in the manuscript should be regarded as previously derived composite results rather than independently recalculated values from the currently archived basin-level dataset. The distinction is particularly important for the interpretation of the study: the groundwater-level comparison and associated quality-controlled statistics are directly traceable to the cited Environmental Status Reports, whereas the complete numerical reconstruction of all five IGSA components requires additional underlying datasets. Future applications of IGSA should archive the station-level groundwater series, SGI calculation series, recovery indicators, basin abstraction and recharge estimates, normalization bounds, component scores, and final weighted aggregation so that every published IGSA value can be independently reproduced.

4. RESULTS

The Results are organised in two explicitly separated parts. Section 4.1 presents the IGSA results first, including the basin-level component audit, quality-controlled groundwater-level evidence for the two reference periods, basin-specific IGSA interpretation, and the quantitative sensitivity and external benchmark analyses. Section 4.2 then presents contextual environmental and anthropogenic pressures, including wastewater treatment, decentralized sanitation, surface-water quality, tourism growth, and hydroclimatic conditions. The contextual indicators are used to interpret the spatial patterns identified by IGSA but are not treated as direct causal inputs to the IGSA calculation.

4.1. IGSA results and groundwater conditions

4.1.1. Overall basin-level IGSA results

The IGSA results (**Table 2**) are considered first so that the integrated stress ranking and its reconstructable groundwater-level component are presented independently of contextual pressure evidence. The basin-specific subsections below therefore focus on groundwater-level change, variability, and the documented IGSA score. Environmental and anthropogenic pressures are deliberately discussed separately in Section 4.2. Across the six basin systems, the previously reported composite IGSA results identify Ishëm–Erzen as the highest-stress system (0.82; very high), followed by Shkumbin (0.66; high), Seman (0.60; high), and Vjosa (0.44; moderate). Exact historical composite scores are not available for Drin–Buna and Mati in the archived component-level material. The directly reconstructable groundwater-level-change component (Tn) follows the same broad pattern for the four basins with documented composite scores, with Tn values of 1.000, 0.941, 0.824, and 0.706, respectively. This comparison is descriptive: the composite scores remain previously reported historical results, whereas Tn is directly calculated from the quality-controlled basin-level means.

Table 2.

Basin-level IGSA component reconstruction status and previously reported composite scores.

Basins	ΔH (m)	Tn	Vn	Dn	Rn	Pn	Previously reported IGSA	Stress class
Drin–Buna	−0.4	0.529	NR	NR	NR	NR	Not available	—
Mati	+0.5	0.000	NR	NR	NR	NR	Not available	—
Ishëm–Erzen	−1.2	1.000	NR	NR	NR	NR	0.82	Very high
Shkumbin	−1.1	0.941	NR	NR	NR	NR	0.66	High
Seman	−0.9	0.824	NR	NR	NR	NR	0.60	High
Vjosa	−0.7	0.706	NR	NR	NR	NR	0.44	Moderate

Tn is directly calculated from the quality-controlled reference-period mean changes using Eq. (4). Vn, Dn, Rn and Pn are marked NR (not reproducible from the archived material) because the underlying component-level inputs and/or exact aggregation and normalization parameters are unavailable. The four numerical IGSA scores shown are the previously reported historical composite results and are not independently recalculated from the currently archived dataset. Drin–Buna and Mati do not have exact historical composite scores available in the archived material.

4.1.2. Drin–Buna River Basin

The Drin–Buna system is the largest river basin system considered in this study and forms part of the wider transboundary Drin Basin, which extends across Albania, Kosovo, Montenegro, and North Macedonia. The system includes the Drin and Buna/Bojana rivers and is hydrologically connected with the Prespa, Ohrid, and Skadar/Shkodra lake systems. These transboundary linkages are relevant to the integrated management of surface water, groundwater, and associated ecosystems (Pano, 2008; Dreshaj et al., 2012; UNECE, 2025).

The comparative analysis of characteristic groundwater levels (**Table 3** and **Fig. 2**) indicates relatively stable conditions between the two reference periods. The average minimum, mean, and maximum groundwater levels changed from −11.7, −8.9, and −6.2 m in 2005–2009 to −6.5, −9.3, and

−12.4 m in 2020–2024, respectively. These changes indicate a modest deepening of groundwater levels, particularly in the recent period, but do not suggest a pronounced basin-wide decline.

A modest increase in groundwater level fluctuation amplitude is also observed during 2020–2024, indicating greater short-term variability. The observed change is reported here as a groundwater-level characteristic of the two reference periods; its underlying drivers are considered separately in Section 4.2. Overall, the Drin–Buna Basin exhibits comparatively stable groundwater conditions. An exact historical composite IGSA score is not available in the archived component-level dataset; therefore, no numerical composite score is assigned here. The groundwater-level evidence nevertheless indicates a modest increase in variability and supports continued monitoring within this transboundary system.

Table 3.

Groundwater levels for the periods 2005–2009 and 2020–2024, by river basin.

Basin	Period	Minimum (m)	Mean (m)	Maximum (m)	Amplitude (m)
Drini-Buna	2005–2009	−11.7	−8.9	−6.2	5.5
	2020–2024	−12.4	−9.3	−6.5	5.9
Mati	2005–2009	−9.8	−7.4	−5.1	4.7
	2020–2024	−9.1	−6.9	−4.6	4.5
Ishëm-Erzen	2005–2009	−9.8	−6.7	−3.9	5.9
	2020–2024	−11.2	−7.9	−4.8	6.4
Shkumbin	2005–2009	−6.9	−4.2	−1.8	5.1
	2020–2024	−8.1	−5.3	−2.6	5.5
Seman	2005–2009	−6.1	−3.6	−1.2	4.9
	2020–2024	−7.0	−4.5	−1.9	5.1
Vjosa	2005–2009	−5.8	−4.7	−3.8	2.0
	2020–2024	−6.6	−5.4	−4.4	2.2

Source: Agjencia Kombëtare e Mjedisit (AKM), Environmental Status Reports for the corresponding reference periods (2005–2009 and 2020–2024); authors' basin-level reconstruction and quality control.

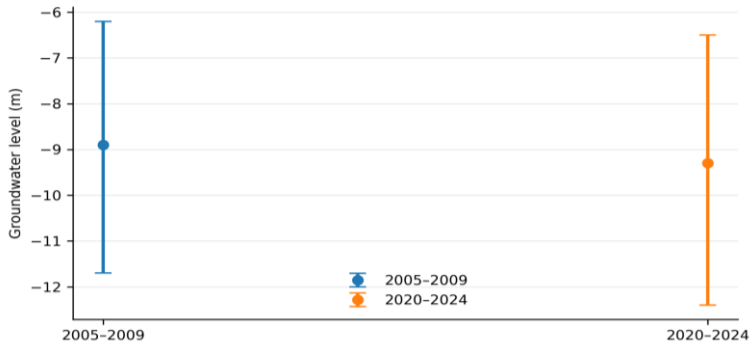


Fig. 2. Groundwater-level range (minimum–maximum) and mean for the Drin–Buna Basin, comparing the two reference periods. Source: authors' graph based on the Albanian Environmental Status Reports (2005–2009 and 2020–2024).

4.1.3. Mati River Basin

The Mati River Basin extends across northern central Albania and is drained primarily by the Mati River and its main tributaries, including the Fan and Uraka rivers. The Mati River originates in the Martanesh area and has a total length of approximately 144 km and a catchment area of about 2,441 km². Groundwater contributions account for approximately 30% of the river's total annual flow (Pano, 2008). The comparative analysis of groundwater levels in the Mati River Basin (**Table 3** and **Fig. 3**)

indicates relatively modest changes between the two reference periods. The average minimum, mean, and maximum groundwater levels changed from −9.8, −7.4, and −5.1 m in 2005–2009 to −9.1, −6.9, and −4.6 m in 2020–2024, respectively. These changes indicate a slight rise in groundwater levels across all three characteristic measures, rather than a basin-wide decline.

The fluctuation amplitude also decreased slightly, from 4.7 m in 2005–2009 to 4.5 m in 2020–2024, indicating relatively stable groundwater level variability between the two periods. The observed changes therefore do not indicate a pronounced deterioration in groundwater level conditions, although seasonal and local variations may remain important.

In terms of integrated assessment, an exact historical composite IGSA score for the Mati Basin is not available in the archived component-level dataset and is therefore not assigned here. The groundwater-level comparison indicates relatively stable conditions, with a slight upward shift in the reported mean level and a small reduction in fluctuation amplitude.



Fig. 3. Groundwater-level range (minimum–maximum) and mean for the Mati River Basin, comparing the two reference periods. Source: authors' graph based on the Albanian Environmental Status Reports (2005–2009 and 2020–2024).

4.1.4. Ishëm–Erzen River Basin

The Ishëm–Erzen River Basin includes the Tirana–Ishëm plain and the Erzen depression, while its eastern part is dominated by mountainous areas including Mount Dajti and Mali me Gropa, which influence local hydrological and groundwater recharge processes (Pano, 2008). The analysis of groundwater level data for the Ishëm–Erzen Basin (**Table 3** and **Fig. 4**) indicates a pronounced decline between the two reference periods. The average minimum, mean, and maximum groundwater levels changed from −9.8, −6.7, and −3.9 m in 2005–2009 to −11.2, −7.9, and −4.8 m in 2020–2024, respectively. The consistent downward shift across all three characteristic levels indicates a substantial deterioration in groundwater level conditions compared with the other investigated basins.



Fig. 4. Groundwater-level range (minimum–maximum) and mean for the Ishëm–Erzen River Basin, comparing the two reference periods. Source: authors' graph based on the Albanian Environmental Status Reports (2005–2009 and 2020–2024).

The fluctuation amplitude increased from 5.9 m in 2005–2009 to 6.4 m in 2020–2024, indicating a modest increase in groundwater level variability. Together with the downward shift in characteristic

groundwater levels, this identifies a more pronounced change in hydrodynamic conditions than observed in the less affected basin systems. The contextual environmental and anthropogenic pressures relevant to this pattern are considered separately in Section 4.2. The integrated assessment gives an IGSA value of 0.82 for the Ishëm–Erzen Basin, placing it in the very high groundwater stress category according to the classification in **Table 1**. This is the highest IGSA value among the six investigated basin systems and identifies Ishëm–Erzen as the highest-priority basin in the integrated stress ranking.

4.1.5. Shkumbin River Basin

The Shkumbin River Basin, located in central Albania, represents an important hydrological and hydrogeological system extending from the mountainous interior to the Adriatic lowlands. The basin encompasses diverse climatic and hydrogeological conditions, while its aquifers provide groundwater for drinking water supply, industry, and agricultural irrigation (Pano, 2008).

The comparative analysis of groundwater levels in the Shkumbin Basin (**Table 3** and **Fig. 5**) indicates a clear downward shift between the two reference periods. The average minimum, mean, and maximum groundwater levels changed from −6.9, −4.2, and −1.8 m in 2005–2009 to −8.1, −5.3, and −2.6 m in 2020–2024, respectively. The consistent decrease across all three characteristic levels indicates a pronounced deterioration in groundwater level conditions during the recent period.

The groundwater level fluctuation amplitude increased from 5.1 m in 2005–2009 to 5.5 m in 2020–2024, indicating a modest increase in groundwater level variability. The combined downward shift and increased variability indicate a stronger change in groundwater conditions than in the more stable basin systems. Interpretation should take into account the heterogeneity of the basin and the spatial distribution of monitoring points.

The integrated assessment gives an IGSA value of 0.66 for the Shkumbin Basin, placing it in the high groundwater stress category according to the classification in **Table 1**. The basin therefore represents one of the more stressed groundwater systems among those investigated, consistent with its pronounced downward shift in groundwater levels and increased variability.



Fig. 5. Groundwater-level range (minimum–maximum) and mean for the Shkumbin River Basin, comparing the two reference periods. Source: authors' graph based on the Albanian Environmental Status Reports (2005–2009 and 2020–2024).

4.1.6. Seman River Basin

The Seman River Basin encompasses important alluvial groundwater systems associated with the Korçë, Berat, and Fier sub-basins. These systems are characterized by interactions among precipitation, surface water and groundwater, with basin-scale hydrodynamic conditions varying across the associated aquifer systems (Pano, 2008).

The comparative analysis of groundwater levels in the Seman Basin (**Table 3** and **Fig. 6**) indicates a consistent downward shift between the two reference periods. The average minimum, mean, and maximum groundwater levels changed from −6.1, −3.6, and −1.2 m in 2005–2009 to −7.0, −4.5, and

−1.9 m in 2020–2024, respectively. The decrease across all three characteristic levels indicates a gradual deterioration in groundwater level conditions during the recent period.
The groundwater level fluctuation amplitude increased slightly from 4.9 m in 2005–2009 to 5.1 m in 2020–2024, indicating a modest increase in groundwater level variability. The observed downward shift and increased variability place Seman among the basin systems showing a clearer change in groundwater conditions between the two reference periods. The integrated assessment gives an IGSA value of 0.60 for the Seman Basin, placing it in the high groundwater stress category according to the classification presented in **Table 1**.



Fig. 6. Groundwater-level range (minimum–maximum) and mean for the Seman River Basin, comparing the two reference periods. Source: authors' graph based on the Albanian Environmental Status Reports (2005–2009 and 2020–2024).

4.1.7. Vjosa River Basin

The Vjosa River originates in the Pindus Mountains in Greece and forms a transboundary river system shared by Greece and Albania. The river basin extends across approximately 6,706 km², of which about 4,365 km² lie within Albania, and includes the Vjosa and Drinos valleys and associated alluvial and carbonate groundwater systems. Its transboundary character makes the basin particularly relevant to integrated management of groundwater, surface water, and associated ecosystems (Pano, 2008). The comparative analysis of groundwater levels in the Vjosa Basin (**Table 3** and **Fig. 7**), based on monitoring data from the Quaternary aquifers of the Vjosa and Drinos valleys, indicates a consistent but relatively modest downward shift between the two reference periods. The average minimum, mean, and maximum groundwater levels changed from −5.8, −4.7, and −3.8 m in 2005–2009 to −6.6, −5.4, and −4.4 m in 2020–2024, respectively. The consistent decrease across all three characteristic levels indicates a gradual deterioration in groundwater level conditions, although the magnitude of change is lower than that observed in Ishëm–Erzen and Shkumbin.



Fig. 7. Groundwater-level range (minimum–maximum) and mean for the Vjosa River Basin, comparing the two reference periods. Source: authors' graph based on the Albanian Environmental Status Reports (2005–2009 and 2020–2024).

The groundwater level fluctuation amplitude increased slightly from 2.0 m in 2005–2009 to 2.2 m in 2020–2024, indicating relatively limited change in groundwater level variability. The combination

of a modest downward shift and limited change in fluctuation amplitude suggests comparatively stable hydrodynamic conditions, although continued monitoring is important given the basin's hydroclimatic variability and transboundary character.

The integrated assessment gives an IGSA value of 0.44 for the Vjosa Basin, placing it at the moderate groundwater stress category according to the classification presented in **Table 1**. This is among the lower IGSA values obtained for the six investigated basin systems.

4.1.8. Sensitivity, uncertainty and external benchmark

The quantitative robustness analysis focused on the reconstructable groundwater-level change component because the archived historical material does not contain the complete Vn, Dn, Rn and Pn inputs required for a full five-component uncertainty propagation. When each basin-level ΔH value was perturbed independently within ±0.05 m, representing half the 0.1-m reporting precision, the Monte Carlo analysis (200,000 realizations) produced narrow uncertainty intervals for Tn and preserved the basin ranking in all realizations. The 95% intervals were 0.490–0.569 for Drin–Buna, 0.000–0.000 for Mati, 1.000–1.000 for Ishëm–Erzen, 0.898–0.987 for Shkumbin, 0.782–0.866 for Seman, and 0.666–0.747 for Vjosa. Thus, the ordering implied by the groundwater-level-change component is robust to the tested rounding uncertainty. A conditional weight-sensitivity test was also performed for the four basins with documented historical composite IGSA scores. Varying the Tn weight from 0.10 to 0.30 while redistributing the remaining weight equally among the other four components changed the reported composite scores as follows: Ishëm–Erzen 0.797–0.842, Shkumbin 0.625–0.695, Seman 0.572–0.628, and Vjosa 0.407–0.473, respectively. The basin ordering was unchanged across the tested weight range, but the categorical class was not stable for all basins: Ishëm–Erzen changes from high to very high at approximately wTn = 0.111, while Seman changes from moderate to high at wTn = 0.20. Shkumbin remains high and Vjosa remains moderate across the tested range. This result shows that the ranking is robust to the tested Tn-weight variation, while classification near category boundaries is weight-sensitive.

As an external benchmark, the four documented IGSA scores were compared with the mean surface-water quality class for 2018–2025, an indicator not included in IGSA. The mean quality classes were 5.00 for Ishëm–Erzen, 4.75 for Seman, 2.88 for Shkumbin, and 2.13 for Vjosa. The Spearman rank correlation between IGSA score and mean surface-water quality class was ρ = 0.80 (exact two-sided permutation p = 0.333; n = 4), indicating a strong positive rank-order association but not statistical significance at conventional levels. The benchmark therefore provides supportive spatial consistency rather than formal validation. The rank mismatch between Seman and Shkumbin also demonstrates that IGSA captures dimensions beyond surface-water quality and should not be interpreted as a surrogate for a single environmental pressure.

Table 4.

Quantitative uncertainty and conditional weight-sensitivity results.

Basin	Tn baseline	Tn 95% interval	Rank retained	IGSA, wTn=0.10	IGSA, wTn=0.20	IGSA, wTn=0.30
Drin–Buna	0.529	0.490–0.569	100%	N/A	N/A	N/A
Mati	0.000	0.000–0.000	100%	N/A	N/A	N/A
Ishëm–Erzen	1.000	1.000–1.000	100%	0.797	0.820	0.842
Shkumbin	0.941	0.898–0.987	100%	0.625	0.660	0.695
Seman	0.824	0.782–0.866	100%	0.572	0.600	0.628
Vjosa	0.706	0.666–0.747	100%	0.407	0.440	0.473

The Tn 95% intervals result from 200,000 Monte Carlo perturbations of ΔH within ±0.05 m. Rank retained denotes the proportion of realizations preserving the baseline stress ranking. The last three columns show the documented historical composite score under Tn weights of 0.10, 0.20 and 0.30, respectively, with the remaining weight redistributed equally; these values are conditional sensitivity results and do not reconstruct missing component scores.

Surface-water quality was not used as an IGSA input. Higher class numbers represent poorer quality. Spearman ρ = 0.80 (exact two-sided permutation p = 0.333; n = 4). The comparison is an external benchmark rather than causal validation.

Table 5.

External benchmark of the four documented IGSA scores against mean surface-water quality class, 2018–2025.

Basin	Previously reported IGSA	Mean surface-water quality class, 2018–2025	IGSA rank	Benchmark rank
Ishëm–Erzen	0.82	5.00	1	1
Seman	0.60	4.75	3	2
Shkumbin	0.66	2.88	2	3
Vjosa	0.44	2.13	4	4

4.2. Contextual environmental and anthropogenic pressures

4.2.1. Wastewater treatment infrastructure

Despite ongoing investments in wastewater treatment infrastructure, groundwater resources in Albania remain exposed to environmental pressures associated with incomplete treatment coverage, aging facilities, and limitations in treatment performance. Recent Albania-specific research has also highlighted the continuing technical and institutional challenges associated with the development, monitoring, and management of wastewater treatment systems (Gjinali et al., 2026).

The national inventory compiled for this paper includes twenty (20) wastewater treatment plants (WWTPs), either operational or under construction (**Table 7**), with a combined design capacity of approximately 1.29 million population equivalents (p.e.). However, nominal design capacity does not necessarily translate into effective treatment or continuous reduction of pollution loads. Several facilities are non operational, under construction, or undergoing upgrading, while others have been in service for more than a decade. Consequently, the installed or planned capacity should not be interpreted as equivalent to the volume of wastewater effectively treated under current operating conditions. The availability of tertiary treatment remains limited. Only a limited number of facilities in the inventory are identified as providing tertiary treatment, with several designed primarily for phosphorus removal rather than combined nitrogen and phosphorus removal. This limitation is particularly relevant for nutrient control and the protection of receiving surface water and groundwater systems.

Based on site investigations conducted by the authors and benchmarking indicators calculated by AKUK in 2026, the currently effective treatment capacity is estimated at approximately 831,000 p.e. This represents only a portion of the wastewater load generated and collected nationally. Approximately 29% of the collected wastewater load receives some level of treatment, while only around 5% of the total load is reported to undergo tertiary treatment. These figures indicate a substantial gap between wastewater collection, effective treatment capacity, and treatment level. In areas where wastewater is insufficiently treated or treatment systems are not operational, the resulting pollution loads may contribute to pressure on receiving water bodies and, where hydrogeological conditions permit, on groundwater bodies, particularly in vulnerable coastal and alluvial aquifers (Gjinali et al., 2026). Future investments in new and upgraded WWTPs are expected to improve treatment capacity and performance. Until these systems become operational and achieve the intended treatment levels, however, wastewater management will remain an important environmental pressure on surface water and potentially connected groundwater systems.

4.2.2. Anthropogenic Pressure from Decentralized Wastewater Systems

Decentralized wastewater systems, particularly septic tanks and other on-site sanitation systems, represent an additional source of anthropogenic pressure on Albania's water resources. Approximately half of the population, corresponding to around 1.7 million inhabitants or approximately 460,000 households, is not connected to centralized sewerage systems, with an estimated 500,000 septic tanks nationwide.

The environmental significance of these systems depends on their design, construction, maintenance, and desludging practices. Where septic systems are inadequately designed or poorly maintained, insufficiently treated wastewater may infiltrate surrounding soils and potentially reach

groundwater, particularly in areas with shallow groundwater tables, permeable soils, or vulnerable alluvial and karstic aquifers. Irregular desludging and inappropriate disposal of septic tank sludge may create additional pathways for nutrient, organic, and microbiological pollution to reach surface water and groundwater systems. The absence of a comprehensive national monitoring and management database further constrains effective oversight of decentralized sanitation systems.

In the Albanian context, limited sewerage coverage, extensive reliance on on-site sanitation, inadequate maintenance, and weaknesses in monitoring and sludge management represent an important anthropogenic pressure on groundwater resources, particularly in coastal and alluvial aquifers exposed to increasing population and seasonal tourism pressures. Strengthening decentralized wastewater management through registration and monitoring of septic systems, regular desludging, safe sludge disposal, and progressive expansion of sewerage networks is therefore important for reducing pressure on groundwater and improving wastewater management performance.

4.2.3. Pressure from urban wastewater discharges on surface water quality

Surface water quality across Albania's six major river basin systems during 2018–2025 shows substantial spatial and temporal variability, reflecting differences in urbanisation, wastewater collection and treatment, industrial activity, hydrological conditions, and other anthropogenic pressures (AKM, 2025).

Table 6.

Surface water quality classes in Albania's major river basin systems, 2018–2025.

Year	Drin-Buna	Ishëm-Erzen	Shkumbin	Seman	Vjosa	Mati
2018	III	V	IV	V	II	III
2019	IV	V	III	V	III	II
2020	IV	V	III	V	II	III
2021	IV	V	II	V	II	III
2022	III	V	III	V	II	II
2023	IV	V	III	IV	II	II
2024	III	V	II	IV	II	II
2025	III	V	III	V	II	II

Source: Albanian National Environmental Agency (AKM), Environmental Status Reports (2018–2025).
Legend: Class 1 = High; Class 2 = Good; Class 3 = Moderate; Class 4 = Poor; Class 5 = Bad.

High Class 1	Good Class 2	Moderate Class 3	Poor Class 4	Bad Class 5

The data indicates persistent pressure in several river basins (**Table 6**). The Ishëm–Erzen system consistently records Classes IV–V, corresponding to poor to bad surface water quality, while the Seman Basin also frequently falls within Classes IV–V. These patterns are consistent with sustained anthropogenic pressures, including urban wastewater discharges, inadequate wastewater treatment, and other point and diffuse source pollution. In contrast, the Vjosa and Mati basins generally exhibit better surface water quality, predominantly within Classes II–III, while Drin–Buna and Shkumbin show greater interannual variability.

The observed differences are relevant to groundwater assessment because many Albanian aquifers are hydraulically connected with rivers and other surface water bodies. Deterioration in surface water quality may therefore represent an associated environmental pressure on connected groundwater systems, particularly in permeable alluvial settings, areas with shallow groundwater tables, or systems with strong groundwater–surface water interactions (Winter, 1995; Sophocleous, 2002; Ma et al., 2024). However, the available data do not permit direct quantification of the contribution of surface water pollution to groundwater quality; these relationships are therefore interpreted as contextual rather than causal.

Table 7.

Wastewater treatment plants in Albania: treatment level, design capacity, construction year, and operational status (August 2026).

WWTPs	Treatment Level (T1 = primary; T2 = secondary; T3 = tertiary	Treatment capacity (PE)	Construction, Year	Operational status 2026
Durres	T3 (P removal not N)	250,000	2013/2027-2029	In Operation / Upgrade
Kavaja	T2	75,000	2005/2020	Not operational
Gramsh	T1	16,500	2016	In Operation
Spille	T2	20,000	2026	Under Construction
Korce	T2	86,000	2012	In Operation
Shkoder	T3 (P removal not N)	36,000	2027-2029	New Under Construction
Shiroka	T2	2,000	2011	In Operation
Velipoja	T3 (P removal not N)	85,000	2012	In Operation
Saranda	T1 + 1/2xT2	29,000 / 60,000	2012/2026-2029	Not operational / Upgrade
Pogradec	T3 (P removal not N)	50,000	2006/2017	In Operation
Himare	T2	16,000	2025	In Operation
Vlore	T1	90,000(W)*-160,000(S)	2004/2018	In Operation
Lezhe	T1 + 1/2xT2	51,000 / 60,000	2011/2026-2029	In Operation / Upgrade
Gjiri i Lalzit	T3	15,000	2021	In Operation
Orikum	T2	53,000	2014/2026	Not operational
Green Coast	T2	1,500	2023	In Operation
Dhermi	T2	3,000		Under Construction
Tirana	T2	350,000		Under Construction
Bulqiza	T2	8,845	2022	In Operation
Berat	T3	45,000		New Under Construction

Notes: *W-winter; S-summer. Source: Authors' calculations using data provided by the Albanian National Water Supply and Sewerage Agency (AKUK, 2026).

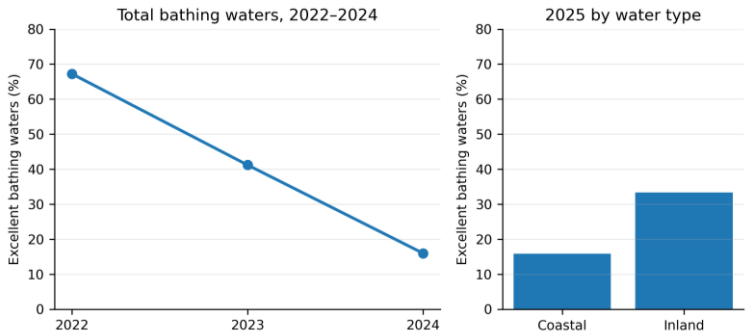


Fig. 8. Excellent bathing water quality in Albania: total bathing waters, 2022–2024, and 2025 results by water type. Source: European Environment Agency (EEA, 2025, 2026).

The EEA bathing water data provide an additional indicator of wastewater-related environmental pressure in Albania's coastal and inland recreational waters. **Fig. 8** separates the 2022–2024 national series from the 2025 coastal and inland results because the latest EEA reporting is presented by water type. The proportion of Albanian bathing waters classified as "excellent" declined from 67.2% in 2022 to 41.2% in 2023 and 16.0% in 2024. In 2025, 15.9% of coastal bathing waters and 33.3% of inland bathing waters were classified as excellent (EEA, 2025; EEA, 2026). The EEA identifies untreated or insufficiently treated wastewater, together with short-term hydrological events and runoff, as important factors influencing bathing water quality.

These findings are particularly relevant to Albania's coastal and alluvial groundwater systems. Where groundwater and surface water bodies are hydraulically connected, wastewater-related contaminants may contribute to pressures on receiving water through groundwater and surface water exchange. The bathing water results therefore provide complementary evidence of environmental pressure but are not used as direct inputs to the IGSA indicator. Taken together, wastewater treatment limitations, decentralised sanitation systems, and surface water quality pressures indicate that wastewater management remains an important environmental pressure on Albania's water resources, particularly in densely populated, urbanised, coastal areas.

4.2.4. Pressure from tourism growth on water resources and the environment

Tourism in Albania expanded substantially over the period 2016–2025, despite temporary fluctuations associated with external factors. As shown in **Fig. 9**, visitor numbers increased progressively between 2016 and 2019, followed by a sharp decline in 2020 associated with the COVID-19 pandemic and restrictions on international mobility. Tourism subsequently recovered rapidly, with continued growth from 2021 to 2025 and record visitor numbers in the most recent years (INSTAT, 2026).

The sustained growth of tourism represents an increasing potential seasonal pressure on water resources and related environmental infrastructure, particularly in coastal and urban areas. The concentration of visitors during the summer season can increase water demand and wastewater generation over relatively short periods, placing additional pressure on water supply systems, sewerage networks, wastewater treatment facilities, and receiving water bodies. These pressures are particularly relevant in coastal and alluvial areas, where groundwater is an important source of water supply and shallow aquifers may be sensitive to changes in abstraction and wastewater management.

The relationship between tourism growth and groundwater stress is not assumed to be direct or uniform across the country. Tourism is therefore considered a contextual anthropogenic pressure that may intensify existing water resource pressures through increased seasonal abstraction, wastewater generation, and demand for water-related services. The magnitude of this pressure depends on local hydrogeological conditions, infrastructure capacity, wastewater treatment performance, and the seasonal distribution of water demand. The rapid expansion of tourism therefore provides an important context for interpreting groundwater conditions and for future water resource planning, particularly in coastal basins such as Drin–Buna, Ishëm–Erzen, and Vjosa. Continued tourism growth should be accompanied by improvements in water supply efficiency, wastewater collection and treatment, groundwater monitoring, and integrated water resource management to limit increasing seasonal pressure on vulnerable groundwater systems.

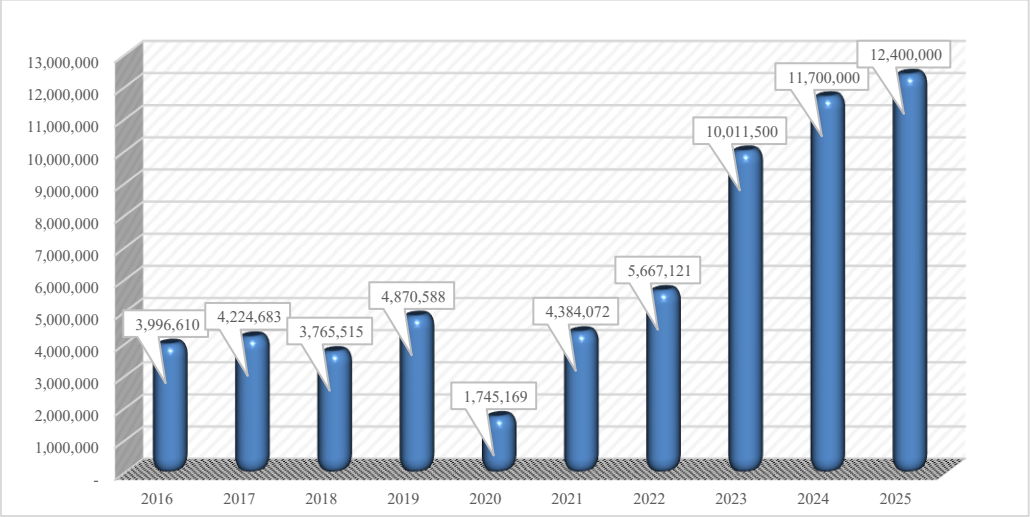


Fig. 9. Tourism sector development in Albania, 2016–2025. Source: INSTAT (2026), Tourism Statistics.

4.2.5. Hydroclimatic pressure on water resources and groundwater

The annual precipitation and temperature series for Albania over 2010–2025 provide an important hydroclimatic context for water resources and groundwater systems (**Fig. 10**; World Bank, 2025). While precipitation shows no clear long-term increase, temperatures show an overall increase, which may increase evapotranspiration and reduce the fraction of precipitation available for effective groundwater recharge. The magnitude of these effects, however, depends on local climatic and hydrogeological conditions. Hydroclimatic variability may therefore contribute to reduced groundwater replenishment and increased water stress, particularly in systems already affected by groundwater abstraction and other anthropogenic pressures (Taylor et al., 2013; Fan et al., 2023).

These hydroclimatic changes indicate increasing vulnerability of water resources to climate variability and change and highlight the importance of incorporating hydroclimatic conditions into groundwater assessment and long-term water resource planning (Fan et al., 2023).

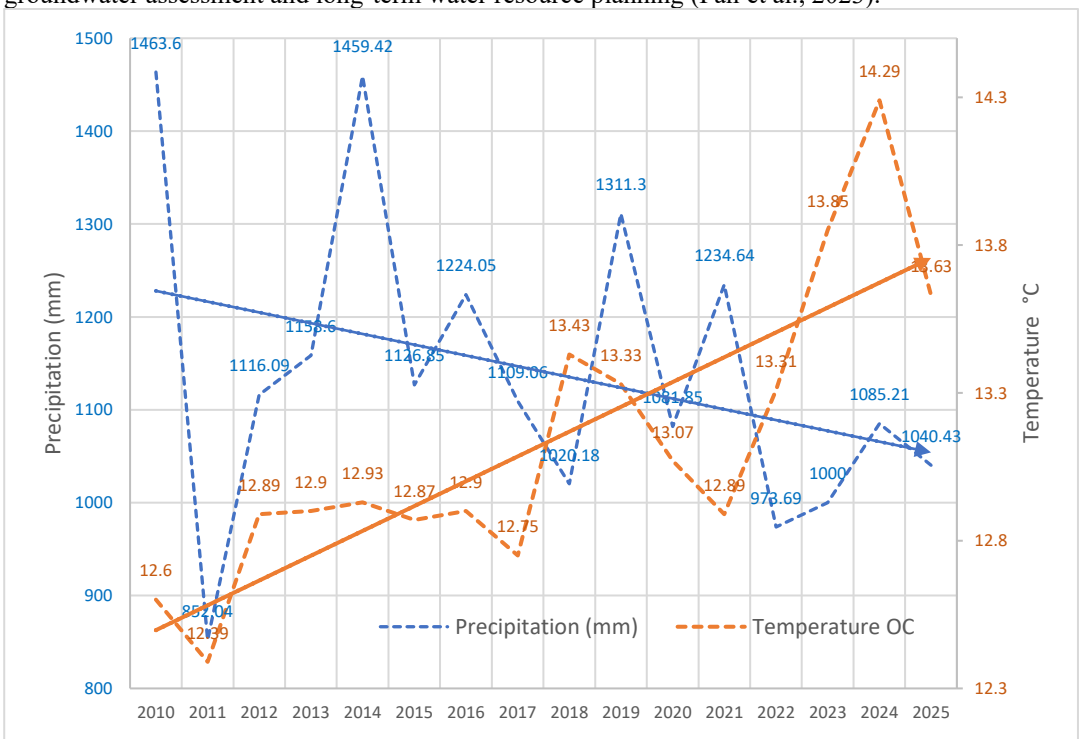


Fig. 10. Annual precipitation and annual mean temperature in Albania, 2010–2025. Source: World Bank (2025), Climate Change Knowledge Portal.

5. DISCUSSION

5.1. Interpretation of the integrated stress pattern and component drivers

The basin-scale results indicate a clear spatial differentiation in groundwater stress, with the highest previously reported composite score in Ishëm–Erzen (IGSA = 0.82), followed by Shkumbin (0.66), Seman (0.60) and Vjosa (0.44). These values should be interpreted together with the reconstruction status reported in **Table 3**: the composite scores for these four systems are previously derived historical results, whereas the groundwater-level-change component (Tn) is directly reconstructable from the quality-controlled basin-level means. The corresponding Tn values are 1.000, 0.941, 0.824 and 0.706, respectively. Thus, the strongest documented spatial signal is a downward shift in groundwater levels, but the integrated IGSA ranking is conceptually broader than this single component because it also incorporates variability, drought, recovery capacity and abstraction relative to recharge. The component architecture is useful because the five dimensions represent different manifestations of groundwater stress. Tn represents a relatively slow state

response: a persistent downward shift in the mean groundwater level between the two reference periods is interpreted as greater stress. Vn represents hydrodynamic variability and therefore captures the possibility that a system can experience larger seasonal or interannual excursions even when its period-average level changes little. Dn is intended to capture groundwater drought severity through the Standardised Groundwater level Index (SGI), which was developed specifically to standardise groundwater-level anomalies and identify groundwater drought characteristics across monitoring records (Bloomfield & Marchant, 2013). Rn represents the capacity of the system to recover after depletion, while Pn represents the pressure associated with abstraction relative to natural recharge. These components are mechanistically related but not redundant: a basin may have a relatively stable mean level while experiencing large fluctuations or recurrent drought, or it may have substantial recharge but still experience stress when abstraction is high relative to that recharge.

For the present dataset, however, only Tn can be interpreted as a fully reconstructed numerical component. The archive does not contain the complete SGI series and fitting parameters, the recovery-event series and operational definition, or the basin-specific abstraction/recharge values and normalization bounds needed to recalculate Dn, Rn and Pn; the exact rule used historically to aggregate the two period-specific amplitudes into Vn is also unavailable. Consequently, the Discussion does not assign observed numerical magnitudes to these unavailable components. Instead, they are interpreted as the mechanisms that the original IGSA architecture was designed to capture. This distinction is essential for avoiding circular interpretation of the previously reported composite scores. The quantitative robustness results reinforce the interpretation of the directly reconstructable component. Perturbing ΔH by ± 0.05 m, corresponding to half the reported 0.1 m precision, preserved the Tn ranking in 100% of the 200,000 Monte Carlo realizations. Moderate changes in the Tn weight (0.10–0.30) also left the documented composite stress classes unchanged for Ishëm–Erzen, Shkumbin, Seman and Vjosa. The results therefore support the stability of the broad spatial pattern, but not the claim that uncertainty in all five IGSA components has been fully quantified.

5.2. Hydrogeological mechanisms underlying the basin differences

The spatial pattern is consistent with the fact that Albania contains strongly heterogeneous groundwater systems, including intergranular alluvial aquifers, karst systems and fractured-rock settings. Such systems differ in storage, hydraulic connectivity, recharge pathways, residence time and sensitivity to abstraction. Eftimi et al. (2023) emphasise the heterogeneity of Albanian aquifers and the importance of river recharge, coastal processes, karst vulnerability and transboundary conditions in groundwater management. This heterogeneity provides a hydrogeological explanation for why the same reference-period change in a basin-average groundwater level should not automatically be interpreted as equivalent local stress.

The Ishëm–Erzen result is particularly consistent with the known behaviour of the Tirana–Ishmi alluvial aquifer. The aquifer contains hydraulically connected gravelly units and is recharged by precipitation and by several rivers in its unconfined sectors. Recent hydrogeological work reports substantial groundwater-level variation in sectors with intensive abstraction and identifies the interaction between pumping, river recharge and urban development as important controls on the system (Dindi et al., 2024). These mechanisms provide a plausible physical context for the pronounced downward shift ($\Delta H = -1.2$ m) and increased amplitude (5.9 to 6.4 m) observed in the present basin-level reconstruction. They do not, however, demonstrate that abstraction or urbanisation caused the observed historical shift, because the present dataset does not contain the component-level abstraction, recharge and station-level time series required for attribution.

The Mati result illustrates the opposite response. The mean groundwater level shifts upward by +0.5 m and the amplitude decreases slightly from 4.7 to 4.5 m. This does not indicate that the aquifer is free from pressure; rather, it shows that the two-period groundwater-level component does not identify a deterioration at basin-scale. This interpretation is compatible with the documented importance of river–aquifer exchange in the Mati coastal plain. Kumanova et al. (2014) showed that the Mati alluvial aquifer is strongly connected to river recharge and that hydraulic head and sediment conditions influence recharge sustainability. The Mati case therefore demonstrates why a basin-level

stress assessment should not infer stress from abstraction or coastal setting alone when the observed groundwater-level response is comparatively stable.

In Shkumbin and Seman, the combination of downward groundwater-level shifts and modestly increased fluctuation amplitudes suggests a broader change in hydrodynamic conditions. Both systems contain important lowland/alluvial groundwater resources, but their internal hydrogeological heterogeneity means that a basin average can mask contrasting local responses. The Tn values of 0.941 for Shkumbin and 0.824 for Seman are therefore best interpreted as screening signals that warrant spatially resolved follow-up, rather than as proof of uniform aquifer depletion. This is particularly important because the archived Shkumbin earlier-period definition still requires source verification, as documented in the supporting workbook.

The Vjosa system provides an instructive contrast. It shows a downward mean-level shift of −0.7 m but a comparatively small change in amplitude (2.0 to 2.2 m) and a previously reported composite score of 0.44. The Vjosa and Drinos valleys contain alluvial and carbonate groundwater systems and are hydraulically connected to a highly dynamic river environment. Published work on the lower Vjosa alluvial aquifer has also identified groundwater extraction and coastal processes as relevant to groundwater conditions, including the risk of seawater intrusion under intensive exploitation (Dindi & Shehu, 2023). The comparatively lower integrated score should therefore not be interpreted as absence of vulnerability; rather, it indicates a lower relative screening signal within the six-basin comparison.

Drin–Buna similarly shows a relatively modest downward shift ($\Delta H = -0.4$ m) but a small increase in amplitude from 5.5 to 5.9 m. Its transboundary character and connection with the wider Drin–Buna hydrological system mean that groundwater conditions are influenced by processes operating across basin boundaries. The stability of the basin-average signal should therefore be interpreted alongside the need for coordinated monitoring and data exchange, rather than as evidence that local aquifers are uniformly stable.

Across all six systems, the mechanisms discussed above are plausible hydrogeological explanations, not statistically demonstrated causal pathways. Groundwater–surface water exchange, recharge from precipitation and rivers, abstraction-induced hydraulic gradients, evapotranspiration, and changes in land use can operate simultaneously (Winter, 1995; Sophocleous, 2002; Ma et al., 2024). This is precisely why an integrated framework can be useful for screening, but it also explains why the present basin-level dataset cannot substitute for aquifer-scale water-balance modelling.

5.3. Comparison with the groundwater-stress literature and methodological contribution

The comparison shows that IGSA is best understood as an integration architecture rather than as a replacement for established physical groundwater-stress metrics. The groundwater footprint approach of Gleeson et al. (2012) expresses groundwater use in relation to recharge and groundwater-dependent environmental requirements through a spatial footprint. Renewable Groundwater Stress (RGS) of Richey et al. (2015b) similarly focuses on groundwater use relative to renewable groundwater availability. Both have a strong water-balance interpretation and are particularly informative where abstraction, recharge, and environmental requirements can be quantified consistently. IGSA retains this perspective through Pn, but Pn is only one of five dimensions and is interpreted jointly with observed groundwater-state change, variability, drought and recovery.

The Total Groundwater Stress framework of Richey et al. (2015a) differs conceptually again: it relates groundwater storage and depletion to a depletion timescale. It therefore provides a storage-based perspective on how long a system may remain within a specified depletion criterion. IGSA does not reproduce this calculation. Its Rn component is instead intended to represent recovery behaviour after stress, so the two concepts are related at the level of system resilience but are not numerically equivalent. This distinction prevents the composite framework from being presented as a substitute for storage or water-balance assessment.

SGI-based groundwater-drought assessment provides the clearest contrast in temporal focus. Bloomfield and Marchant (2013) standardised groundwater-level anomalies to identify drought severity and persistence. IGSA adopts this established drought concept through Dn but does not

redefine SGI. The additional contribution is architectural: drought is placed alongside groundwater-level change, variability, recovery and abstraction-to-recharge pressure so that a basin can be screened even when stress is expressed through several partially independent mechanisms.

IGSA also differs from generic composite-indicator frameworks not in the general mathematics of normalization and weighting, which are well established (OECD/European Union/EC-JRC, 2008; Saisana et al., 2005; Greco et al., 2019), but in their application to a groundwater-specific five-dimensional architecture with a consistent stress orientation. The common 0–1 scale makes heterogeneous indicators comparable, while the additive equation and equal 20% weights make the decision rule explicit. Min–max normalization is deliberately transparent but relative to the comparison population; it is therefore not a universal threshold system. The conceptual distinction among the approaches is summarized in **Table 8**.

Table 8.

Conceptual comparison of IGSA with established groundwater-stress and composite-indicator approaches.

Framework	Primary concept and core inputs	IGSA relationship	Methodological implication
Groundwater Footprint (Gleeson et al., 2012)	Spatial footprint needed to sustain groundwater use, accounting for recharge and groundwater-dependent environmental requirements.	Pn is a related use-versus-recharge dimension; IGSA also includes observed state, variability, drought and recovery.	IGSA is not a new footprint metric; its contribution is integration of the pressure dimension with complementary state/response dimensions.
Renewable Groundwater Stress (RGS) (Richey et al., 2015b)	Groundwater use relative to renewable groundwater availability; requires compatible abstraction/use and renewable-availability estimates.	Pn is conceptually close to RGS, but is only one of five IGSA dimensions.	Extends a physical pressure ratio into a multi-dimensional screening architecture rather than replacing RGS.
Total Groundwater Stress (TGS) (Richey et al., 2015a)	Groundwater storage and depletion expressed through a depletion criterion/timescale.	Rn addresses recovery capacity after stress and is not numerically equivalent to storage/depletion TGS.	Adds recovery behaviour as a distinct dimension while retaining the need for storage/water-balance analysis where required.
Standardised Groundwater-level Index (SGI) (Bloomfield & Marchant, 2013)	Standardized groundwater-level anomalies used to characterize drought severity and persistence; requires a groundwater-level time series.	Dn adopts the established SGI drought concept without redefining it.	Adds drought as one component of a broader stress architecture rather than proposing a new drought index.
Composite-indicator methodology (OECD/European Union/EC-JRC, 2008; Saisana et al., 2005; Greco et al., 2019)	Normalization, weighting, aggregation and robustness procedures for integrating multiple indicators.	Provides the methodological foundation for IGSA's common 0–1 scale, equal weights, additive aggregation and sensitivity analysis.	IGSA's domain-specific contribution is the groundwater five-dimension architecture and its explicit audit/transfer workflow.
IGSA (this study)	Comparative groundwater-stress screening using Tn (state change), Vn (variability), Dn (drought), Rn (recovery) and Pn (abstraction/recharge).	All five dimensions are oriented to higher stress, normalized to 0–1 and aggregated with equal 20% weights.	Application-oriented novelty: transparent integration and auditability for heterogeneous basin systems. Robustness is demonstrated where inputs are reconstructable; full historical validation remains constrained by archived data availability.

Note: The comparison is conceptual and methodological; it does not imply that the component-level datasets required by each framework are available for all six Albanian basins in the present archive.

The framework has been evaluated at the level that the available evidence permits. Robustness was tested by propagating ±0.05 m reporting uncertainty through Tn using 200,000 Monte Carlo realizations, and conditional weight sensitivity was tested by varying the Tn weight from 0.10 to 0.30 for the four basins with documented historical composite scores. The basin ordering remained unchanged, although the categorical class was weight-sensitive near the classification boundaries for Ishëm–Erzen and Seman. An external benchmark against mean surface-water quality gave $\rho = 0.80$, with an exact two-sided permutation $p = 0.333$ and $n = 4$, which does not support statistical validation. Moreover, Vn, Dn, Rn and Pn cannot be independently reconstructed from the archived historical material. Accordingly, the evidence supports methodological transparency and robustness of the reconstructable component, not full empirical validation of the five-component index.

The defensible international contribution is therefore application-oriented: this study presents and transparently evaluates a screening-level composite framework for comparing groundwater stress across heterogeneous basin systems using routinely available monitoring and pressure information, and demonstrates its application to Albania. The novelty lies in the explicit integration and auditability of complementary stress dimensions for data-limited basin comparison, not in claiming that groundwater footprint, RGS, TGS, SGI, or composite-indicator mathematics are individually novel.

This positioning also makes the framework reusable as a workflow, provided that its inputs, normalization bounds, weights and validation evidence are recalculated and documented for each new setting.

5.4. Transferability to other data-limited groundwater systems

The main transferable element is the workflow rather than the numerical thresholds or the Albanian ranking. A future application can retain the five-dimensional architecture where monitoring systems provide sufficiently long groundwater records and compatible pressure data. The minimum reproducibility package should include: identified monitoring stations and aquifer units; a documented vertical datum and sign convention; the groundwater time series used for drought and recovery analysis; basin-compatible abstraction and recharge estimates; explicit definitions of recovery events; normalization bounds; component scores; weights; and the final aggregation. These requirements turn IGSA from a country-specific calculation into an auditable workflow that can be reused and independently checked.

Transferability should occur through a staged implementation. First, harmonise station metadata, units, datum and basin boundaries. Second, calculate the raw indicators using locally appropriate time windows and definitions. Third, orient and normalize each indicator to the same stress direction. Fourth, test alternative normalization and weighting choices and report their influence on ranking. Fifth, compare the resulting ranking against independent hydrogeological, drought, water-balance, or environmental evidence. Where a component cannot be supported by adequate data, it should be reported as unavailable rather than reconstructed by assumption, as demonstrated in the present study.

Normalization and weighting must be recalibrated for each target system. Albanian minimum and maximum values should not be transferred automatically because min–max scores depend on the population of systems being compared. Likewise, the equal 20% weights are a transparent default rather than a universal optimum; future studies can test expert-elicited, stakeholder-defined, or data-driven weights. Validation should also be local and independent: the present surface-water benchmark is only an initial consistency check, whereas stronger transferability evidence would require longer station-level records, independent drought/resilience measures, and aquifer-scale water-balance or numerical-model evidence.

The framework is consequently most transferable as a decision-support and prioritisation tool for heterogeneous national monitoring programmes, particularly where data are distributed across institutions or preserved mainly as annual environmental summaries. It is less transferable as a stand-alone estimate of aquifer sustainability because sustainability assessment requires explicit storage, recharge, abstraction, environmental-flow, and, where relevant, coastal density-dependent processes. The Albania application demonstrates the workflow and its audit discipline; it does not establish universal thresholds or weights.

5.5. Limitations, uncertainty and implications for interpretation

Several limitations constrain the strength of inference. First, the groundwater comparison uses two five-year reference periods rather than a continuous station-level time series. The results therefore describe reference-period differences and cannot establish a statistically significant temporal trend. Second, the absence of a consistently documented common vertical datum and complete station metadata limits station-level comparability. Third, basin averaging may conceal local hotspots and differences among aquifer units. Fourth, the exact historical numerical inputs for Vn, Dn, Rn and Pn are unavailable, so the previously reported composite scores cannot be independently recalculated from the archived dataset. This is a data-reproducibility limitation, not evidence that those components are unimportant.

Fifth, equal weighting and min–max normalization introduce methodological dependence. A high score can arise from a combination of moderate component values, while min–max normalization is sensitive to the set of basins included in the comparison. The conditional weight analysis indicates that the four documented composite classifications are stable when the Tn weight is varied between 0.10 and 0.30, but this does not test alternative normalization methods or uncertainty in the missing component values. Sixth, the external benchmark uses only four basins and an indicator that is related to, but distinct from, groundwater stress. It is therefore appropriately treated as supportive benchmarking rather than validation.

These limitations lead to a deliberately conservative interpretation of the results. Ishëm–Erzen is the clearest national screening priority because it combines the largest reconstructed downward groundwater-level shift with the highest previously reported composite score. Shkumbin and Seman also warrant enhanced investigation, while Vjosa and Drin–Buna require continued monitoring because moderate basin-average signals can coexist with local or seasonal vulnerability. Mati illustrates the importance of retaining basins with stable or improving reference-period groundwater levels in the comparison, since the framework is intended to discriminate among systems rather than assume that all systems are deteriorating.

For management, the results support a tiered monitoring strategy: intensified station-level observation and abstraction assessment in high-priority systems; targeted investigation of recharge and groundwater–surface water interactions; improved registration of abstraction and recharge; and stronger integration of groundwater evidence into river-basin and transboundary planning. The contextual wastewater, tourism and hydroclimatic evidence should be used to formulate hypotheses and management priorities, but not to retroactively attribute causality to the IGSA scores. Future research should test the framework against longer station-level series, aquifer-scale water balances, independent drought and resilience metrics, and alternative composite-index formulations across hydrogeologically contrasting regions.

Taken together, these limitations define the scope of the contribution: IGSA should be interpreted as a transparent comparative screening architecture whose value is tested through reproducibility documentation, component-level robustness analysis, and external benchmarking, while its full predictive or sustainability validity remains an open empirical question for future applications.

6. CONCLUSIONS

This study provides a basin-scale screening assessment of groundwater stress across six major hydrogeological systems in Albania by comparing the common reference periods 2005–2009 and 2020–2024 and applying the Integrated Groundwater Stress Assessment (IGSA). The directly reconstructed groundwater-level component identifies the strongest downward reference-period shifts in Ishëm–Erzen (−1.2 m), Shkumbin (−1.1 m) and Seman (−0.9 m), while the previously reported composite IGSA scores are 0.82, 0.66, 0.60 and 0.44 for Ishëm–Erzen, Shkumbin, Seman and Vjosa, respectively.

The principal contribution is application-oriented: IGSA provides a transparent composite architecture that places groundwater-state change, variability, drought, recovery and abstraction relative to recharge on a common 0–1 stress scale, with explicit normalization, weighting, robustness

testing and reproducibility requirements. It was developed to support comparative screening under heterogeneous and incomplete national monitoring data. The method does not replace aquifer-scale water-balance modelling, drought analysis or site-specific investigation, and the historical composite scores for four basins remain previously reported results because the archived component-level inputs for Vn, Dn, Rn and Pn cannot be independently reconstructed.

The findings support intensified station-level monitoring and abstraction assessment in Ishëm–Erzen, Shkumbin and Seman; improved groundwater–surface-water and recharge investigations; stronger registration of abstraction and recharge; and closer integration of groundwater evidence into river-basin and transboundary planning. Future applications should use longer station-level series, locally recalibrated normalization and weighting, and independent hydrogeological validation. The contextual wastewater, tourism and hydroclimatic evidence should guide management hypotheses and priorities but should not be interpreted as independently quantified causal inputs to IGSA.

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