

Bridging Albanian monitoring and Water Framework Directive oriented assessment: A surface water quality index

Enkelejda Gjinali^{1*}, Vanela Gjeçi², Santino Spahiu³, Fationa Sinojmeri¹,
Oltion Marko¹, Gea Gjinali Baduni³, Tamas Koncsos⁴

¹ Department of Environmental Engineering, Polytechnic University of Tirana, Rruga Muhamet Gjollështa 54, 1023, Tirana, Albania

² Department of Directorate for Environmental Data Management, Chemicals, Laboratory Analysis, and Innovation, Sector of Laboratory Analysis and Contract Monitoring, National Environmental Agency, Street “Sami Frasheri”, No. 4, Tirana, Albania

³ Department of Hydraulics and Hydrotechnics, Polytechnic University of Tirana, Rruga Muhamet Gjollështa 54, 1023, Tirana, Albania

⁴ Department of Environmental and Sanitary Engineering, Budapest University of Technology and Economics, 1111, Műgyetem rkp. 3. Budapest, Hungary

* Corresponding author's e-mail: enkelejda.gjinali@fin.edu.al

ABSTRACT

The implementation of the European Union Water Framework Directive (WFD) presents an important methodological challenge for countries whose established environmental monitoring systems are not yet fully harmonised with WFD compatible surface water body delineation and assessment structures. This situation is particularly relevant for EU candidate countries, where existing station-based monitoring programmes must increasingly support integrated river basin assessment and alignment with the environmental acquis. This study addresses this challenge by developing a composite surface water quality index (SWQI) capable of integrating existing monitoring observations into a consistent quantitative river basin assessment while accommodating incomplete spatial harmonisation of water body delineation. The proposed framework integrates six physicochemical parameters—dissolved oxygen (DO), biochemical oxygen demand (BOD₅), ammonium (NH₄), nitrite (NO₂), nitrate (NO₃) and total phosphorus (P-total)—through normalization, weighting and aggregation into a common 0–100 scale. A bounded continuous normalization approach was developed for observations exceeding Class V boundaries, preserving information on the severity of extreme observations while constraining scores within the defined scale. The framework was applied to 33 monitoring stations with complete six parameter datasets across five Albanian river basin reporting units. Mat recorded the highest basin level SWQI (98.79), followed by Drin-Bunë (97.40), Shkumbin (94.29) and Seman (93.33), whereas Ishëm-Erzen recorded the lowest value (68.54). Sensitivity testing showed that the basin ranking remained unchanged under the specific parameter weighting, aggregation and normalization scenarios examined, although absolute SWQI values varied under some methodological configurations, particularly for Ishëm-Erzen. Comparison with the national environmental assessment further demonstrated that the SWQI provides complementary information rather than reproducing or replacing regulatory ecological status classification. The study demonstrates that station-based monitoring observations can be transformed into a transparent and reproducible basin level assessment even where WFD oriented spatial harmonisation is still progressing. Beyond Albania, the framework has potential as a transferable methodological approach for EU candidate countries undergoing alignment with the WFD acquis, particularly where established monitoring systems need to be progressively integrated with WFD compatible water body delineation and assessment structures.

Keywords: surface water quality, water quality index, river basin assessment, Water Framework Directive, bounded continuous normalization, composite indicator, environmental monitoring, European Union candidate countries.

INTRODUCTION

Surface water quality assessment is essential for understanding the environmental condition of river systems, identifying major pollution pressures and supporting evidence-based water resource management. Rivers integrate the effects of natural processes and multiple anthropogenic pressures, including urban wastewater, agricultural runoff, industrial activities and diffuse nutrient inputs. Because these pressures may vary substantially along river networks, effective water quality assessment requires monitoring approaches capable of capturing both local conditions and broader spatial patterns at the river basin level.

The European Union Water Framework Directive (WFD) 2000/60/EC established an integrated framework for the protection and assessment of European surface waters based on river basin management and the assessment of surface water bodies. Within this framework, assessment is not limited to individual physicochemical measurements but involves the integration of monitoring information, ecological status, pressures and management measures within a defined spatial structure. Surface water bodies represent a fundamental unit for WFD oriented status assessment, while river basins provide the broader management framework within which water bodies, pressures and measures are considered (European Commission, 2003; European Parliament and Council, 2000).

Composite water quality indices (WQIs) have evolved through a range of numerical and classification-based approaches (Brown et al., 1970; Smith, 1989). Subsequent work extended these to parameter specific and classification-based formulations (Pesce and Wunderlin, 2000; Sarganekar and Deshpande, 2003), and to aggregation-based frameworks applied at basin scale (Lumb et al., 2006; Sutadian et al., 2016). By combining multiple parameters into a common scale, WQIs can facilitate spatial comparison, communication of complex monitoring results and identification of areas requiring greater management attention (Sutadian et al., 2016; Uddin et al., 2021). However, the construction of a composite index requires methodological decisions concerning parameter selection, normalization, weighting and aggregation (OECD et al., 2008; Sutadian et al., 2016). These decisions can substantially influence the resulting index values and classifications, particularly when monitoring datasets contain highly

variable or extreme observations. Consequently, the robustness of a composite index should be explicitly evaluated rather than assumed (Dobbie and Dail, 2013; OECD et al., 2008).

This issue is particularly relevant in Albania, where the national surface water monitoring system and the development of the WFD oriented water body framework are progressing in parallel. National environmental monitoring data are primarily collected and reported through monitoring stations and national river basin reporting structures, whereas the water resources management framework is progressively incorporating more detailed river basin, sub-basin and surface water body delineation. As a result, the available national monitoring information does not yet provide a uniformly harmonised spatial relationship between every monitoring station, formally delineated surface water body and river basin management unit. This creates a practical methodological challenge for integrating existing monitoring observations into a consistent WFD oriented assessment framework.

At the same time, Albania has an increasingly valuable national evidence base for surface water assessment. The National Environment Agency (NEA; Albanian acronym AKM) provides monitoring observations and water quality assessments for the principal river systems (National Environment Agency, 2025), while recent research has demonstrated the applicability of integrated WQI based approaches to individual Albanian river systems. In particular, Gjeçi et al. (2025b) applied physicochemical, nutrient and biological assessment approaches in the Erzeni–Ishmi Basin, demonstrating substantial spatial variation in water quality conditions. The water resources management and geospatial frameworks are also progressively developing more detailed water body delineation and ecological status information (Council of Ministers of the Republic of Albania, 2023; State Authority for Geospatial Information, 2025).

However, a nationally structured composite framework capable of integrating station based monitoring observations across multiple Albanian river basin reporting units, while explicitly evaluating the effects of normalization, weighting and aggregation choices, remains insufficiently developed.

Against this background, this study develops a SWQI framework specifically adapted to the Albanian national monitoring and river basin

reporting context. The proposed framework integrates six physicochemical parameters DO, BOD₅, NH₄, NO₂, NO₃ and total phosphorus (P-total) into a common 0–100 scale. The index is calculated at monitoring station level and subsequently aggregated to the river basin level, while retaining the possibility of linking monitoring observations to formally delineated surface water bodies where such information is available.

A particular methodological feature of the proposed framework is the use of bounded continuous normalization for observations exceeding the Class V boundary. This approach retains information on the severity of extreme observations while constraining normalized scores to the defined 0–100 range. In addition, the study explicitly evaluates the sensitivity of the resulting SWQI to alternative parameter weighting schemes, aggregation methods and normalization treatments. This is intended to assess the sensitivity of the observed spatial patterns to methodological assumptions inherent in composite index construction.

The study has five main objectives: (i) to develop a transparent and reproducible composite SWQI framework for integrating selected physicochemical monitoring parameters in Albanian river systems; (ii) to apply the index to available national monitoring data and quantify surface water quality at monitoring station and river basin levels; (iii) to evaluate the sensitivity of the SWQI to alternative normalization, weighting and aggregation choices; (iv) to identify spatial differences in surface water quality among Albanian river basins and monitoring locations; and (v) to compare the resulting SWQI patterns with national environmental assessments and available WFD oriented ecological status information.

The study therefore contributes a practical and adaptable composite assessment framework for Albania, particularly relevant to a monitoring context in which station based national observations coexist with the progressive development of a more harmonised WFD oriented water body framework. The proposed SWQI is intended as a complementary analytical tool rather than a replacement for regulatory ecological status classification, providing an integrated quantitative signal that can facilitate spatial comparison, interpretation of multiple physicochemical parameters and identification of basins requiring greater attention. By explicitly testing normalization, weighting and aggregation choices, the

study also seeks to provide a transparent basis for evaluating the robustness and applicability of composite surface water quality assessment in a national river basin context.

STUDY AREA

River basin framework and spatial organisation

Albania is characterized by a dense river network and substantial spatial variability in topography, hydrology, land use and anthropogenic pressures. Surface water management and assessment are therefore organised within a river basin framework. Importantly, however, different national information systems have historically used different spatial reporting structures, reflecting their respective institutional mandates and data collection purposes.

The water resources management framework distinguishes seven river basin regions: Drin-Bunë, Mat, Ishëm, Erzen, Shkumbin, Seman and Vjosa. This seven-basin structure is established in the current national regulatory framework and provides the basis for river basin management and the delineation of associated water resources. Decision of the Council of Ministers (DCM) No. 636, dated 5 November 2025, explicitly establishes these seven river basin regions and provides for the delineation of sub-basins in the Mat, Ishëm and Erzen regions (Council of Ministers of the Republic of Albania, 2025).

The national environmental monitoring framework, however, reports river monitoring information using six basin categories, with Ishëm-Erzen treated as a combined reporting unit alongside Drin-Bunë, Mat, Shkumbin, Seman and Vjosa. This difference is important for the integration of monitoring and water management datasets and is directly relevant to the development of a harmonised surface water quality assessment framework.

The present study therefore adopts the six-basin reporting structure of the AKM monitoring dataset for the quantitative analysis, while recognising the seven-basin structure used by the water resources management framework. The distinction is maintained explicitly rather than attempting to reconcile the two systems by imposing a spatial classification that is not present in the original monitoring data.

From river basins to WFD surface water bodies

The Water Framework Directive establishes the surface water body as a fundamental unit for the assessment and management of surface water status (European Commission, 2003; European Parliament and Council, 2000). Ideally, a monitoring dataset intended for WFD oriented assessment would therefore establish a consistent spatial relationship between the monitoring station, the delineated water body and the river basin management unit.

In Albania, this spatial structure is being progressively developed. The current water resources framework explicitly provides for the delineation of sub-basins and other water resources, while WFD oriented water body information has already been developed for selected river basin areas. For example, the State Authority for Geospatial Information (ASIG), in cooperation with the Water Resources Management Agency (AMBU), has published ecological status datasets for surface water bodies derived from the Ishëm and Erzen River Basin Management Plans for 2024–2029 (Council of Ministers of the Republic of Albania, 2023; State Authority for Geospatial Information, 2025). These datasets include delineated surface water bodies and their ecological status information.

However, such water body delineation and identification are not yet consistently represented across the entire national monitoring dataset used in this study. The AKM monitoring programme is primarily structured around monitoring locations and annual observations and therefore does not provide a uniformly applicable Water Body ID for all stations included in the present analysis. No Water Body ID was assigned or inferred for the 33 monitoring stations included in the quantitative analysis where an unambiguous linkage to a formally delineated surface water body was not available.

This situation creates an important methodological challenge: a national surface water quality index should be capable of using the information that is actually available from the monitoring network without introducing artificial water body boundaries or identifiers.

Accordingly, the spatial structure adopted in this study is: Monitoring Station → River Basin → Year → Water Quality Parameter. Where a formally delineated Water Body ID is available, it is

retained as an additional spatial attribute. Where it is not available, no artificial Water Body ID is assigned. This approach allows the proposed SWQI to operate within the existing national monitoring system while remaining compatible with the progressive development of the WFD water body framework.

Surface water monitoring network

The national surface water monitoring programme provides the principal observational basis for the present assessment. AKM reports monitoring stations across the major Albanian river systems and provides water quality classifications based on the monitoring observations. The 2025 monitoring framework covers the six reporting categories Drin-Bunë, Mat, Ishëm-Erzen, Shkumbin, Seman and Vjosa.

The map illustrates (Figure 1) the spatial distribution of the national river monitoring network and the reported water quality classes of the monitored locations. It provides the geographical context for the observations used in this study and

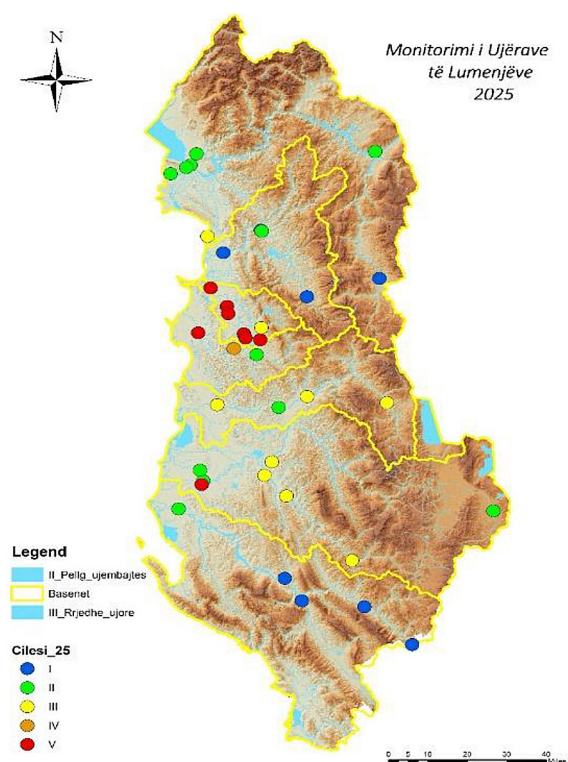


Figure 1. Spatial distribution of surface water monitoring stations and reported water quality classes in Albania, 2025. Source: National Environment Agency (AKM), Environmental Status Report 2025 (RGJM 2025) (National Environment Agency, 2025)

demonstrates the spatial coverage of the national monitoring programme.

For the quantitative SWQI assessment, complete numerical observations for all six selected physicochemical parameters were available for 33 monitoring stations distributed across five basin reporting units: Drin-Bunë, Mat, Ishëm-Erzen, Shkumbin and Seman.

Vjosa remains part of the national six basin monitoring framework and the overall study context but was not included in the quantitative SWQI calculation because numerical observations for NO₂, NO₃ and P-total required for the six-parameter index were not available in the dataset used for this study. No values were imputed for the missing parameters.

Rationale for the basin level SWQI approach

The differences between the national monitoring structure and the progressively developing WFD water body framework provide an important methodological rationale for the present study.

Rather than requiring complete water body delineation as a prerequisite for quantitative assessment, the proposed SWQI is designed to operate directly from observed monitoring station data, while retaining the possibility of linking stations to formally delineated water bodies where such information is available.

The analytical framework therefore consists of two complementary spatial levels:

- Monitoring station level, where the six selected physicochemical parameters are normalised and aggregated to calculate the SWQI,
- Basin level, where station-level SWQI values are aggregated to provide a comparative representation of the physicochemical monitoring signal across the included monitoring stations within each basin.

The basin-level aggregation should therefore be understood as a network-based comparative indicator rather than a spatially weighted estimate of the mean condition of all surface waters within a basin. This distinction reflects the structure of the available monitoring data and avoids assigning hydrological or spatial weights that cannot be consistently derived for all monitoring locations.

This structure is particularly relevant for countries in which the transition towards fully harmonised WFD oriented monitoring and water

body delineation is still progressing (European Commission, 2003; European Parliament and Council, 2000). It allows existing monitoring data to be transformed into a transparent and reproducible composite indicator without assuming a level of spatial harmonisation that is not yet consistently available.

The proposed approach is therefore intended not as a substitute for WFD ecological status assessment, but as a complementary methodology capable of integrating heterogeneous monitoring observations into a consistent quantitative framework. It can also provide a basis for future integration with WFD water body datasets as national delineation and spatial identification become progressively more comprehensive.

DATA AND METHODS

Data sources and monitoring network

The analysis was based exclusively on the station-specific surface water monitoring values reported by the National Environment Agency (NEA/AKM) in the 2025 Environmental Status Report (RGJM 2025). The values were used as reported in the official source dataset, without additional statistical aggregation or annual averaging by the authors. All 198 numerical observations used in the quantitative SWQI analysis correspond to the 2025 monitoring year and comprise 33 monitoring stations × 6 selected physicochemical parameters. The present study therefore treats each reported station-parameter value as the source observation for 2025 and does not reinterpret it as an annual mean, median, maximum, or other statistic unless such aggregation is explicitly specified in the NEA source.

The assessment considered the six river basin areas represented in the NEA monitoring framework: Drin-Bunë, Mat, Ishëm-Erzen, Shkumbin, Seman, and Vjosa. The RGJM 2025 reports monitoring results for individual river stations and provides their physicochemical quality assessment according to a five-class reference framework.

For the development of the proposed SWQI, six physicochemical parameters were selected: DO, BOD₅, NH₄, NO₂, NO₃, and total phosphorus (P-total). These parameters were selected to represent complementary aspects of oxygen conditions, organic pollution, and nutrient enrichment and because corresponding Class I–V reference

thresholds are reported in the national surface water assessment framework.

The final quantitative SWQI dataset comprised 33 monitoring stations from five river basins—Drin-Bunë, Mat, Ishëm-Erzen, Shkumbin, and Seman—for which numerical observations were available for all six selected parameters. A complete-case approach was used: a monitoring station was included in the quantitative SWQI calculation only when numerical observations were available for all six selected parameters. Stations with one or more missing parameters were excluded from the quantitative SWQI calculation rather than being assigned imputed values. This criterion was applied uniformly across all basin reporting units to ensure that the same six-parameter index was calculated for every included station. Because complete-case selection may affect the spatial representativeness of the quantitative dataset, the resulting SWQI is interpreted as an assessment of the monitored stations meeting the six-parameter completeness criterion rather than as an unconditional assessment of the entire river basin.

Selection of water quality parameters

The SWQI incorporates six physicochemical parameters: DO, BOD₅, NH₄, NO₂, NO₃, and P-total. These parameters were selected to represent three complementary dimensions of surface water quality: DO, organic and nitrogenous pollution (BOD₅ and NH₄), and nutrient enrichment (NH₄, NO₂, NO₃ and P-total), consistent with the use of physicochemical parameters in composite surface water quality assessment (Sutadian et al., 2016; Uddin et al., 2021).

The parameter selection was defined a priori based on three criteria. First, the selected parameters had to be consistently available within the national surface water monitoring dataset used in

the study. Second, each parameter had to have corresponding national Class I–V reference boundaries that could be incorporated into a common normalization framework. Third, the selected parameters were required to provide complementary information on the principal physicochemical dimensions represented in the available monitoring framework, namely oxygenation, organic pollution, and nutrient enrichment.

Other parameters available within the broader monitoring programme were not incorporated into the present SWQI where their observations were not sufficiently consistent across the stations included in the quantitative assessment and/or where directly compatible Class I–V reference boundaries were not available within the source classification framework. This criterion was applied to ensure that the final index could be calculated consistently across monitoring stations without introducing imputation or non-comparable reference scales. The monitoring information and national classification boundaries used as the basis for the present assessment were obtained from the national environmental monitoring framework (National Environment Agency, 2025).

The selected parameters are therefore intended to provide a transparent and reproducible composite representation of the physicochemical water quality information consistently available in the national monitoring system, rather than to represent the full range of ecological or chemical quality elements required for WFD ecological status assessment (European Parliament & Council, 2000).

The national classification framework provides Class I–V reference boundaries for the six selected parameters, which form the reference basis for the normalization procedure described in the normalization of water quality parameters (National Environment Agency, 2025). These boundaries are presented in Table 1.

Table 1. Reference concentration boundaries used for SWQI normalization

Parameter	Class I	Class II	Class III	Class IV	Class V
DO (mg O ₂ /L)	>7	>6	>5	>4	<3
BOD ₅ (mg/L)	<2	<3.5	<7	<18	>18
NH ₄ (mg N/L)	<0.05	<0.30	<0.60	<1.50	>1.50
NO ₂ (mg N/L)	<0.01	<0.06	<0.12	<0.30	>0.30
NO ₃ (mg N/L)	<0.8	<2	<4	<10	>10
P-total (mg P/L)	<0.10	<0.20	<0.40	<1.0	>1.0

Note: National Environment Agency (AKM), Environmental Status Report 2025 (RGJM 2025) (National Environment Agency, 2025).

The reference boundaries in Table 1 reproduce the five-class Albanian physicochemical river water quality classification framework reported by the National Environment Agency (AKM) in the Environmental Status Report 2025 (RGJM 2025). In the present study, these legally and administratively established national reference boundaries are used solely as reference points for SWQI normalization and are not interpreted as WFD ecological status thresholds.

For the numerical normalization procedure, the based reference inequality limits reported in the NEA classification framework were operationalised using the corresponding numerical breakpoints of 7, 6, 5, 4 and 3 mg O₂/L for dissolved oxygen. These numerical breakpoints are used solely for the interpolation procedure developed in this study and do not modify the official NEA classification presented in Table 1.

The five reference classes were not directly adopted as SWQI classes. Instead, they were used as reference points for transforming the measured concentrations into continuous, dimensionless quality scores ranging from 0 to 100.

For the purposes of the proposed SWQI, the five reference classes were assigned the anchor scores shown in Table 2.

The anchor scores presented in Table 2 were defined specifically for the proposed SWQI and represent a methodological scoring convention rather than an official NEA scoring system or a regulatory classification of surface water status. The equally spaced values of 100, 80, 60, 40 and 20 were selected to preserve the ordinal structure of the five national reference classes while providing a simple, transparent and monotonic basis for continuous interpolation between adjacent class boundaries. This approach avoids assigning identical scores to all observations within a class and allows differences in measured concentrations to be retained in the composite index. The anchor values should therefore be interpreted as relative quality scores linked to the national reference framework, rather than as empirically calibrated ecological response functions.

Because the anchor scores are a methodological choice of the present study, their influence on the resulting SWQI was evaluated through

an additional sensitivity analysis. Alternative monotonic anchor-score configurations were applied while keeping the NEA reference concentration boundaries, equal parameter weighting, normalization procedure and arithmetic aggregation unchanged. Although the alternative configurations produced differences in the absolute SWQI values, the basin-level ranking remained unchanged across all tested configurations. The largest variation occurred for Ishëm-Erzen, for which the SWQI ranged from 64.67 to 70.43 across the tested configurations. The results therefore indicate that the principal spatial ranking remained unchanged under the tested anchor-score configurations, while the precise absolute index values and, near an interpretation threshold, the qualitative category may be sensitive to the scoring convention.

Normalization of water quality parameters

Because the six parameters have different measurement units, concentration ranges, and relationships with water quality, the observed values were transformed into dimensionless scores on a common 0–100 scale, with higher scores representing better physicochemical water quality conditions (OECD et al., 2008; Uddin et al., 2021).

A piecewise linear interpolation was applied between adjacent reference class boundaries. For parameters for which increasing concentrations indicate deteriorating water quality (BOD₅, NH₄, NO₂, NO₃, and P-total), the normalized score for an observation located between two consecutive class boundaries was calculated as:

$$N_i = S_L + (S_U - S_L) \frac{C_i - C_L}{C_U - C_L} \quad (1)$$

where: N_i is the normalized score, C_L and C_U are the lower and upper concentration boundaries of the relevant interval, S_L and S_U are their corresponding normalized scores.

For dissolved oxygen, for which higher concentrations represent better water quality conditions, the interpolation direction was reversed:

$$S_L + \frac{(DO_i - DO_L)(S_U - S_L)}{DO_U - DO_L} \quad (2)$$

Table 2. Quality scores assigned to the reference classes

Reference class	Class I	Class II	Class III	Class IV	Class V
Normalized quality score	100	80	60	40	20

where: DO_i is the observed dissolved oxygen concentration, DO_L and DO_U are the lower and upper numerical DO boundaries of the relevant interval; and S_L and S_U are the corresponding lower and upper SWQI anchor scores.

For the numerical normalization procedure, the reference inequality limits reported in the NEA classification framework were operationalised using the corresponding numerical breakpoints of 7, 6, 5, 4 and 3 mg O₂/L for dissolved oxygen. These numerical breakpoints and their corresponding anchor scores are used solely for the interpolation procedure developed in this study and do not modify the official NEA classification presented in Table 1. This procedure preserves information contained in the continuous measured concentrations rather than assigning the same score to all observations falling within a particular reference class.

For dissolved oxygen, observations above the Class I reference boundary of 7 mg O₂/L were assigned the maximum normalized score of 100. This treatment follows directly from the structure of the national reference framework, which defines Class I as >7 mg O₂/L without specifying an upper numerical boundary (National Environment Agency, 2025). Because no higher reference point is available within the national classification framework, a further interpolation interval above 7 mg O₂/L cannot be defined consistently from the available reference classes. Assigning 100 to observations above 7 mg O₂/L therefore represents a pragmatic boundary treatment within the proposed normalization procedure, rather than an assumption that all DO concentrations above 7 mg O₂/L are ecologically equivalent. The approach does not distinguish among higher DO observations, including the maximum observed value of 12.40 mg O₂/L, and this loss of differentiation is recognised as a limitation of the reference-based normalization.

Treatment of observations beyond the Class V boundary

Particular attention was given to observations extending beyond the reported Class V boundary. Three alternative approaches were considered during methodological testing: linear extrapolation beyond Class V, assignment of a fixed Class V score, and bounded continuous

normalization. Treatment of extreme observations is an important methodological consideration in composite indicator construction (OECD et al., 2008).

The bounded continuous normalization approach was retained for the final SWQI because it provides a compromise between two competing requirements for observations exceeding the Class V boundary: retaining information on the relative severity of exceedance and maintaining a bounded 0–100 index. A fixed Class V score would treat all observations beyond the Class V boundary as equivalent and would therefore discard potentially relevant information on the magnitude of severe pollution. In contrast, unrestricted linear extrapolation would preserve proportional differences but could produce negative scores and values outside the defined index range.

The bounded continuous formulation was therefore selected as a mathematical scoring convention that preserves the ordering and relative differentiation of extreme observations while constraining their scores to the 0–20 interval associated with the lowest reference class. This formulation is not intended to represent an empirically established ecological dose-response relationship. The influence of this choice was evaluated through comparison with linear extrapolation and Class V capping, with the resulting basin-level values reported in Table 9.

For parameters for which increasing concentrations represent deteriorating water quality, observations exceeding the Class V boundary were transformed using:

$$N_i = S_V \frac{C_V}{C_i} \quad (3)$$

For dissolved oxygen, observations below the Class V boundary were treated in the opposite direction:

$$N_{DO} = S_V \frac{DO_i}{DO_V} \quad (4)$$

where: DO_V represents the Class V boundary for dissolved oxygen. The resulting score is likewise constrained to the 0–20 interval.

The alternative normalization approaches were subsequently examined through sensitivity analysis. The resulting differences in absolute SWQI values did not alter the overall ranking of the assessed basins.

Parameter weighting

Following normalization, equal weights were assigned to the six parameters:

$$w_i = \frac{1}{6} = 0.1667 \text{ with } \sum_{i=1}^6 w_i = 1 \quad (5)$$

Equal weighting was adopted because the six parameters were considered complementary components of the proposed composite index and the available monitoring dataset did not provide a sufficiently justified basis for assigning objectively different parameter weights (Dobbie and Dail, 2013; OECD et al., 2008).

Equal weighting was nevertheless treated as a methodological assumption rather than an inherent property of the index. Its influence was therefore evaluated through a dedicated weighting sensitivity analysis.

Aggregation and calculation of the SWQI

The final station level SWQI was calculated using weighted arithmetic aggregation:

$$SWQI_s = \sum_{i=1}^6 w_i N_{i,s} \quad (6)$$

where: $SWQI_s$ is the SWQI for monitoring station s , $N_{i,s}$ is the normalized score of parameter i at station s , and w_i is the corresponding parameter weight.

Under equal weighting, Equation 6 becomes:

$$SWQI_s = \frac{N_{DO,s} + N_{BOD_5,s} + N_{NH_4,s} + N_{NO_2,s} + N_{NO_3,s} + N_{P-total,s}}{6} \quad (7)$$

The resulting index theoretically ranges from 0 to 100, with higher values representing better overall water quality conditions.

Arithmetic aggregation was selected as the primary method because it provides a transparent and readily interpretable composite score. However, alternative aggregation methods were tested as part of the sensitivity analysis (Dobbie and Dail, 2013; OECD et al., 2008).

Basin level SWQI

Following calculation of station-level SWQI values, a basin-level index was calculated as the arithmetic mean of the monitoring-station SWQI values within each basin:

$$SWQI_b = \frac{1}{n_b} \sum_{s=1}^{n_b} SWQI_s \quad (8)$$

where: $SWQI_b$ represents the basin level index and n_b is the number of monitoring stations included in basin b .

Equal station weighting was adopted as a deliberate design choice because the available monitoring dataset does not provide a sufficiently consistent basis for assigning weights according to river length, discharge, basin area, water-body size, population, or other spatial representativeness criteria. Under this formulation, each included monitoring station contributes equally to the basin-level indicator. The approach therefore provides a monitoring-network-based comparative representation of the physicochemical conditions observed at the included stations, rather than a spatially weighted estimate of the mean water quality of the entire basin.

This choice is appropriate for the present dataset because the monitoring network is station-based and is not yet consistently linked to formally delineated WFD surface water bodies across the full dataset. Applying spatial or hydrological weights that are not consistently available could introduce additional assumptions and potentially create a false impression of spatial precision. The quantitative analysis therefore retains the observed monitoring network structure and applies the same aggregation rule across all five assessed basins. The resulting basin-level SWQI should consequently be interpreted as a comparative indicator of the water quality conditions represented by the available monitoring network, rather than as a spatially exhaustive estimate of mean water quality across each basin.

To assess the sensitivity of the SWQI to the degree of compensation among parameters, three alternative station-level aggregation methods were applied to the six normalized parameter scores: geometric mean, harmonic mean and minimum/non-compensatory aggregation. In all cases, aggregation was performed first at the monitoring-station level using the final bounded continuous normalized scores, followed by arithmetic averaging of the resulting station-level scores within each basin. Thus, the sensitivity analysis varied only the parameter aggregation rule, while keeping the final bounded continuous normalization, equal parameter weighting and basin-level arithmetic aggregation unchanged (Dobbie and Dail, 2013; OECD et al., 2008).

For the geometric aggregation, the station-level score was calculated as:

$$SWQI_s^{geo} = \left(\prod_{i=1}^6 N_{i,s} \right)^{1/6} \quad (9)$$

where: $N_{i,s}$ is the normalized score of parameter i at monitoring station s .

For the harmonic aggregation, the station-level score was calculated as:

$$SWQI_s^{harm} = \frac{6}{\sum_{i=1}^6 (1/N_{i,s})} \quad (10)$$

For the minimum/non-compensatory approach, the station-level score was defined as:

$$SWQI_s^{min} = \min(N_{1,s}, N_{2,s}, N_{3,s}, N_{4,s}, N_{5,s}, N_{6,s}) \quad (11)$$

For each alternative aggregation method, the resulting station-level scores were subsequently aggregated to the basin level using the arithmetic mean:

$$SWQI_b^* = \frac{1}{n_b} \sum_{s=1}^{n_b} SWQI_s^* \quad (12)$$

where: $SWQI_b^*$ represents the basin-level $SWQI$ under the respective aggregation method and n_b is the number of monitoring stations included in basin b .

Interpretation of SWQI values

The resulting 0–100 $SWQI$ was interpreted using five qualitative categories developed specifically for the proposed composite index. The interpretation thresholds for these categories are presented in Table 3.

These thresholds are interpretative categories developed for the proposed $SWQI$ and are not direct equivalents of the five physicochemical quality classes reported by the NEA or of Water Framework Directive ecological status classes. Their purpose is to facilitate interpretation and comparison of the composite index.

Table 3. Proposed interpretation thresholds for the $SWQI$

SWQI range	Interpretation
90–100	Excellent
70–<90	Good
50–<70	Moderate
25–<50	Poor

The sensitivity of these interpretative boundaries was evaluated by testing alternative threshold configurations. The resulting basin classifications remained unchanged.

Sensitivity and robustness analysis

A multi-dimensional sensitivity analysis was undertaken to evaluate whether the resulting basin assessment was dependent on specific methodological assumptions, consistent with recommended robustness testing principles for composite indicators (Dobbie and Dail, 2013; OECD et al., 2008).

Weighting sensitivity

The equal weighting configuration was compared with alternative weighting scenarios that assigned greater emphasis to dissolved oxygen, organic pollution, nutrients, and a pollution conservative scenario. The parameter weighting schemes used in the sensitivity analysis are presented in Table 4. The alternative weighting scenarios were defined to test the influence of different parameter priorities within the six-parameter framework, with the parameter weights constrained to sum to 1.00. Equal weighting corresponds to 1/6 for each parameter and is displayed as 0.1667 after rounding.

The equal weighting configuration represents the primary formulation of the $SWQI$, whereas the alternative scenarios were used exclusively for sensitivity testing. The resulting basin level $SWQI$ values are presented in Table 7.

Normalization sensitivity

Alternative treatments of observations extending beyond Class V were compared, including linear extrapolation, a fixed Class V floor, and bounded continuous normalization. Although these alternatives produced differences in the absolute $SWQI$ values, the basin-level ranking remained unchanged under the scenarios tested. Bounded continuous normalization was therefore retained for the final index because it preserves information on the severity of extreme observations while maintaining the normalized score within the defined 0–100 range (OECD et al., 2008).

Threshold sensitivity

The sensitivity of the proposed $SWQI$ interpretation thresholds was evaluated using two

Table 4. Parameter weighting schemes used in the SWQI sensitivity analysis

Scenario	DO	BOD ₅	NH ₄	NO ₂	NO ₃	P-total
Equal	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
DO priority	0.30	0.15	0.10	0.10	0.15	0.20
Organic priority	0.25	0.25	0.15	0.05	0.10	0.20
Nutrients priority	0.15	0.15	0.20	0.10	0.20	0.20
Pollution conservative	0.10	0.20	0.20	0.10	0.15	0.25

alternative configurations: 90/75/50/25, in which the Good-category boundary was increased from 70 to 75, and 85/70/50/25, in which the Excellent-category boundary was lowered from 90 to 85. The resulting classifications for all five basins under the proposed and alternative configurations are presented in Table 10. All five basins retained the same qualitative classification under both alternative configurations. Thus, the qualitative interpretation of the current basin-level results was unchanged under the tested threshold configurations. These results indicate stability of the basin classifications with respect to the specific threshold alternatives examined, but do not imply that the interpretation thresholds are universally robust. The sensitivity analysis was limited to the weighting, aggregation, normalization and interpretation-threshold scenarios examined here; other sources of uncertainty, including alternative parameter sets, spatial weighting, temporal aggregation and uncertainty propagation, were not evaluated.

External consistency assessment

To provide an external consistency assessment, the basin level SWQI results were compared with the classifications reported in the 2025 NEA/RGJM assessment (National Environment Agency, 2025). The comparison was conducted to examine whether the spatial pattern identified by the proposed SWQI was broadly consistent with, or meaningfully different from, the national regulatory assessment.

This comparison was not treated as formal validation because the SWQI and the national assessment are based on different assessment frameworks and are not intended to represent identical constructs. The SWQI provides a composite assessment of the physicochemical parameters included in the present study, whereas the national assessment follows the applicable regulatory assessment framework. The comparison was therefore used as an external consistency assessment

rather than as evidence of equivalence between the two assessment approaches.

Data quality control and reproducibility

A final source-to-dataset audit was conducted before the calculation of the final SWQI results. The numerical observations entered into the SWQI dataset were systematically compared with the corresponding station-specific observations reported in the 2025 NEA/RGJM source material. The final quantitative dataset comprised: 33 stations $\times$ 6 parameters = 198 parameter observations.

All 198 observations matched the source data, with no numerical discrepancies identified. The Supplementary Excel dataset provides the corresponding source value for each of the 198 parameter observations together with the station, year, parameter and verification information, allowing the traceability of each observation used in the SWQI calculation to be independently checked.

A second level of quality control verified the calculation sequence from normalized parameter scores to weighted sub-indices, station level SWQI values, basin level averages, and final SWQI interpretation classes.

This two-stage verification provides a reproducible calculation chain from the original monitoring observations to the final basin-level SWQI results. The supplementary workbook provides the 198 parameter observations, station metadata, normalized scores, station-level SWQI calculations, basin-level results and sensitivity outputs through formula-linked calculation sheets, allowing the reported results to be independently checked.

RESULTS

Parameter level results

The parameter level analysis provides an initial overview of the water quality conditions

captured by the six parameters included in the proposed SWQI. The final dataset used for the quantitative assessment comprises complete six-parameter observations for 33 monitoring stations distributed across five river basins, with all observations corresponding to the 2025 monitoring year. The normalized scores were calculated using the final bounded continuous normalization procedure described in the Data and Methods section. Descriptive statistics for the six parameters and their normalized scores are presented in Table 5.

The results show substantial differences in the normalized scores and therefore in the contribution of individual parameters to the composite index. NO_3 and NO_2 recorded the highest mean normalized scores, at 99.34 and 98.36, respectively, followed by DO at 97.09. In contrast, BOD_5 and NH_4 produced considerably lower mean normalized scores of 67.58 and 73.49, respectively, indicating that these parameters exerted the greatest downward influence on the composite index. P-total had an intermediate mean normalized score of 88.90, although its score range indicates the presence of stations with substantially poorer phosphorus conditions.

The parameter level results therefore demonstrate that the high SWQI values observed in several basins do not result from uniformly optimal conditions across all parameters. Rather, they reflect the combined effect of generally high scores for DO, NO_2 and NO_3 and lower scores associated particularly with BOD_5 , NH_4 and, at some locations, P-total.

Station level SWQI results

The final SWQI calculation produced values for 33 monitoring stations across the five quantitatively assessed river basins. The station level results demonstrate both generally high-water quality scores and substantial spatial variability within some basins.

The greatest within basin variability was observed in Ishëm-Erzen, where station level SWQI values ranged from 36.06 at L2 to 96.58 at Er1. This indicates that the basin level result incorporates pronounced spatial differences in the quality conditions observed among individual monitoring locations.

The compensatory behaviour of the arithmetic aggregation is illustrated by station L2 in Ishëm-Erzen, where the maximum observed values of BOD_5 (114.00 mg/L), NH_4 (24.00 mg N/L) and P-total (2.25 mg P/L) occurred simultaneously. These observations resulted in normalized scores of 3.16, 1.25 and 8.89, respectively, while the remaining parameters at the station received substantially higher normalized scores. The resulting station-level SWQI was 36.06. Thus, although the extreme parameter values strongly reduced the composite score, they did not determine it alone, because the arithmetic aggregation permits compensation among parameters.

Seman also showed considerable within basin variability, with station level SWQI values ranging from 73.30 at Gj4 to 97.78 at Se6. In comparison, the Mat basin exhibited relatively homogeneous high scores, ranging from 95.16 at Ma2 to 100.00, while Shkumbin showed a narrower range of 91.44–96.43.

These results indicate that basin-level averaging provides a useful overall measure but can mask substantial spatial heterogeneity between monitoring stations. The complete numerical dataset used for the SWQI calculation is provided in the Supplementary Excel dataset. The dataset contains the station ID and monitoring location, coordinates, basin, river, Water Body ID where an unambiguous identifier is available, year (2025), the six original source measurements (DO, BOD_5 , NH_4 , NO_2 , NO_3 and P-total), measurement units, corresponding normalized scores, and the resulting station-level SWQI. A source-to-dataset audit sheet is also provided,

Table 5. Descriptive statistics of the selected water quality parameters and their normalized scores

Parameter	Mean observed value	Minimum	Maximum	Mean normalized score	Normalized score range
DO (mg O_2 /L)	9.35	1.80	12.40	97.09	12.00–100
BOD_5 (mg/L)	11.66	1.60	114.00	67.58	3.16–100
NH_4 (mg N/L)	2.59	0.013	24.00	73.49	1.25–100
NO_2 (mg N/L)	0.00969	0.0007	0.058	98.36	80.80–100
NO_3 (mg N/L)	0.4965	0.072	1.16	99.34	94.00–100
P-total (mg P/L)	0.1988	0.002	2.25	88.90	8.89–100

documenting the correspondence between each numerical observation and its source value and confirming the consistency of the 198 parameter observations used in the analysis. Water Body IDs are reported only where an unambiguous identifier is available in the source information; no Water Body ID has been inferred where such linkage is unavailable.

Completeness and representativeness of the quantitative dataset

The quantitative SWQI assessment was based on 33 monitoring stations for which complete observations were available for all six selected parameters. Stations with incomplete six-parameter records were not included in the numerical index calculation, and no missing values were imputed. Consequently, the quantitative results represent the physicochemical conditions captured by the complete-case monitoring subset rather than the full monitoring network.

The principal exclusion from the basin-level quantitative assessment was Vjosa, for which numerical observations for NO₂, NO₃ and P-total required for the six-parameter SWQI were not available in the source material. The remaining five quantitatively assessed basin reporting units contained stations meeting the complete-case criterion. Because the available source dataset does not provide a sufficiently consistent set of six-parameter observations for all excluded stations, a formal statistical comparison between included and excluded stations was not undertaken.

The results should therefore be interpreted as monitoring-network-based basin comparisons, rather than as estimates of the condition of every location within each basin. This distinction is particularly relevant for basins with heterogeneous monitoring coverage and supports the interpretation of basin-level SWQI values together with the underlying station-level results.

Basin level SWQI results

The final basin-level SWQI values were calculated as the arithmetic mean of the station-level SWQI values within each basin, with each included monitoring station receiving equal weight. This aggregation provides a network-based comparative representation of the physicochemical conditions captured by the monitoring stations rather than a spatially weighted estimate of basin-wide water quality. The results are presented in Table 6.

The median and interquartile range (IQR) were calculated from the station-level SWQI values to characterize the distribution of observations within each basin. Given the small and unequal numbers of monitoring stations, basin-level differences are interpreted descriptively rather than as evidence of statistically significant differences. The results show a clear descriptive differentiation in the monitoring-network-based SWQI among the five quantitatively assessed basin reporting units. Mat recorded the highest basin level SWQI (98.79), followed by Drin-Bunë (97.40), Shkumbin (94.29), and Seman (93.33). All four basins therefore fall within the proposed SWQI category of Excellent. The relatively close mean SWQI values for Shkumbin (94.29) and Seman (93.33) should be interpreted in conjunction with their station-level distributions rather than as evidence of a statistically significant difference.

In contrast, Ishëm-Erzen recorded a substantially lower SWQI of 68.54, placing it in the Moderate category and clearly distinguishing it from the other four basins.

The results also highlight the importance of considering within basin variability. Despite its relatively high basin level score, Seman contains stations with substantially lower SWQI values. The same pattern is more pronounced in Ishëm-Erzen, where the difference between the highest and lowest scoring stations exceeds 60 SWQI points.

Table 6. Final basin level SWQI results

Rank	River basin	No. of Monitoring stations	Mean SWQI	Median SWQI	IQR	Proposed SWQI class
1	Mat	4	98.79	100.00	1.21	Excellent
2	Drin-Bunë	7	97.40	98.67	1.70	Excellent
3	Shkumbin	4	94.29	94.64	1.38	Excellent
4	Seman	8	93.33	95.90	2.20	Excellent
5	Ishëm-Erzen	10	68.54	63.75	19.57	Moderate

Note: The SWQI classes are interpretation categories developed specifically for the proposed index and are not equivalent to WFD ecological status classes or the national regulatory water-quality classification.

The unequal number of monitoring stations among basins should also be considered when interpreting the basin-level comparison. Ishëm-Erzen is represented by 10 stations, Seman by 8, Drin-Bunë by 7, and Mat and Shkumbin by 4 stations. Because the basin-level SWQI is calculated as an equal-weighted mean of station-level scores, differences in the number and spatial distribution of monitoring stations may influence the representation of within-basin variability. The basin ranking should therefore be understood as a comparison of the physicochemical monitoring signal represented by the available station networks, rather than as evidence of equal spatial representativeness among basins.

Sensitivity and robustness results

Weighting sensitivity

The robustness of the basin level results to parameter weighting was assessed by comparing the equal weighting configuration with four alternative weighting scenarios: DO priority, organic pollution priority, nutrient priority, and a pollution conservative configuration.

Although the absolute SWQI values varied according to the weighting configuration, the basin ranking remained unchanged across all five scenarios. Mat consistently ranked first, while Ishëm-Erzen consistently ranked fifth. This indicates that the principal spatial pattern identified by the SWQI is not dependent on the equal-weighting assumption (Table 7).

Aggregation sensitivity

The sensitivity of the results to the aggregation method was assessed by comparing arithmetic, geometric, harmonic and minimum/non-compensatory aggregation at the station level. For each alternative method, the six normalized parameter scores were first aggregated at each monitoring station, after which the resulting station-level scores were averaged arithmetically within each basin. Thus, the sensitivity analysis varied the parameter aggregation rule while keeping the normalization procedure, parameter weights and basin-level spatial aggregation unchanged. This approach is consistent with recommended robustness testing of composite indicators, where alternative aggregation structures can be examined to assess the influence of compensability on composite results (Dobbie Dail, 2013; OECD et al., 2008). The resulting basin-level SWQI values are presented in Table 8. Using the final bounded continuous normalization, Mat recorded values of 98.79, 98.69, 98.58 and 94.29 under arithmetic, geometric, harmonic and minimum/non-compensatory aggregation, respectively. The corresponding values for Drin-Bunë were 97.40, 97.14, 96.84 and 86.56; for Shkumbin, 94.29, 93.78, 93.23 and 76.07; for Seman, 93.33, 91.80, 89.78 and 71.50; and for Ishëm-Erzen, 68.54, 51.15, 36.72 and 23.53. Despite these differences in absolute values, all four aggregation methods produced the same basin ranking: Mat > Drin-Bunë > Shkumbin > Seman > Ishëm-Erzen.

Table 7. Sensitivity of basin level SWQI to alternative weighting schemes

Basin	Equal weighting	DO priority	Organic priority	Nutrient priority	Conservative
Mat	98.79	98.99	98.36	98.85	98.57
Drin-Bunë	97.40	97.75	96.39	97.54	96.92
Shkumbin	94.29	95.38	92.59	94.46	93.27
Seman	93.33	94.38	91.49	93.19	91.87
Ishëm-Erzen	68.54	72.46	62.88	66.56	62.05

Table 8. Basin-level SWQI results under alternative aggregation methods

River basin	Arithmetic	Geometric	Harmonic	Minimum/non-compensatory
Mat	98.79	98.69	98.58	94.29
Drin-Bunë	97.40	97.14	96.84	86.56
Shkumbin	94.29	93.78	93.23	76.07
Seman	93.33	91.80	89.78	71.50
Ishëm-Erzen	68.54	51.15	36.72	23.53

Normalization sensitivity

The three tested treatments of observations extending beyond the Class V boundary—linear extrapolation, Class V capping and bounded continuous normalization—were compared using the same source observations, parameter weights and aggregation procedure. The resulting basin-level SWQI values are presented in Table 9. The alternative normalization approaches produced differences in absolute SWQI values, particularly for Seman and Ishëm-Erzen, but the basin ranking remained unchanged across all three approaches. The final bounded continuous approach was retained because it preserves information on the severity of observations beyond the Class V boundary while maintaining the normalized score within the defined 0–100 scale.

Threshold sensitivity. The sensitivity of the proposed SWQI interpretation thresholds was evaluated by applying alternative threshold configurations to the final basin-level SWQI values. Because these thresholds are applied after the SWQI calculation, they do not alter the numerical index values. The resulting classifications for all five basins under the tested threshold configurations are presented in Table 10. All five basins retained the same qualitative classification across the tested configurations, indicating that the interpretation of the basin-level results was not sensitive to the threshold alternatives examined. The qualitative classification remained unchanged under the tested interpretation thresholds.

Overall robustness

Taken together, the sensitivity analyses showed that the principal basin-level ranking remained unchanged under the specific methodological configurations tested. Changes in parameter weighting, aggregation method and normalization treatment did not alter the ranking of the five quantitatively assessed basins. Although the absolute SWQI values varied under some alternative configurations, particularly for Ishëm-Erzen, the distinction between the four higher-scoring basins and Ishëm-Erzen as the lowest-scoring basin was consistently preserved. These results indicate that the principal basin-level ranking was not altered by the specific methodological assumptions examined.

External consistency assessment with the national regulatory classification

To provide an external consistency assessment, the basin-level SWQI results were compared with the classifications reported in the 2025 NEA/RGJM assessment (National Environment Agency, 2025). Because both the SWQI normalization and the NEA/RGJM assessment are linked to the national regulatory classification framework, this comparison should not be interpreted as independent validation of the SWQI. It is intended as a diagnostic assessment of the behaviour of the proposed composite index rather than as an assertion that the SWQI categories are equivalent to the national regulatory classification.

Table 9. Basin-level SWQI results under alternative treatments of observations beyond Class V

River basin	Linear extrapolation	Class V capping	Bounded continuous
Mat	98.79	98.79	98.79
Drin-Bunë	97.40	97.40	97.40
Shkumbin	94.29	94.29	94.29
Seman	93.74	93.38	93.33
Ishëm-Erzen	69.49	71.74	68.54

Table 10. Basin-level SWQI classification under alternative interpretation thresholds

River basin	SWQI	Proposed 90/70/50/25	Alternative 90/75/50/25	Alternative 85/70/50/25
Mat	98.79	Excellent	Excellent	Excellent
Drin-Bunë	97.40	Excellent	Excellent	Excellent
Shkumbin	94.29	Excellent	Excellent	Excellent
Seman	93.33	Excellent	Excellent	Excellent
Ishëm-Erzen	68.54	Moderate	Moderate	Moderate

The comparison indicates that the two approaches do not necessarily produce identical assessments. This is expected because the proposed SWQI combines six selected physicochemical parameters into a continuous composite score, whereas the 2025 NEA/RGJM assessment follows its own regulatory classification framework and may be influenced by individual parameter exceedances and monitoring locations (National Environment Agency, 2025).

The most notable difference occurs for the Seman Basin. Despite its high basin-level SWQI of 93.33, corresponding to the proposed Excellent category, the 2025 NEA/RGJM assessment identifies poorer conditions within the basin. The persistence of this difference under the alternative normalization treatments indicates that it cannot be attributed solely to the treatment of observations exceeding the Class V boundary.

The comparison therefore highlights an important characteristic of the proposed SWQI: its compensatory structure can produce a high overall score even when one or more individual parameters or monitoring locations indicate poorer conditions. The SWQI should consequently be interpreted as a complementary composite assessment rather than as a replacement for the regulatory classification. For Ishëm-Erzen, the SWQI provides a more differentiated signal of poorer overall conditions. Its basin-level score of 68.54 places it in the Moderate category, and the basin also displays the largest within-basin variability among the five quantitatively assessed basins. Its consistently low ranking across the sensitivity analyses is also observed.

Vjosa. A numerical SWQI was not calculated for Vjosa. Although Vjosa is included in the six-basin study area and in the qualitative assessment of the NEA monitoring framework, station-specific numerical observations for NO₂, NO₃ and P-total were not available in the source dataset for the required six-parameter calculation. These values were therefore not imputed, and Vjosa was excluded from the quantitative basin ranking.

Summary of the main findings

The results demonstrate a differentiation in surface water quality among the five river basins for which a complete six-parameter SWQI could be calculated. Mat, Drin-Bunë, Shkumbin and Seman recorded Excellent basin-level SWQI values, while Ishëm-Erzen was classified as Moderate.

The parameter-level results indicate that NO₂, NO₃ and DO contributed the strongest positive influence to the composite scores, whereas BOD₅ and NH₄ represented the principal parameters reducing SWQI values, with P-total contributing more strongly at selected stations.

The basin ranking remained unchanged under all tested weighting configurations, aggregation methods and normalization approaches. Although the absolute SWQI values varied under some methodological configurations, particularly for Ishëm-Erzen, the principal basin-level ranking remained stable. The interpretation-threshold sensitivity analysis also showed that the qualitative classification of the five quantitatively assessed basins remained unchanged under the tested threshold configurations. Taken together, these results indicate that the principal basin-level ranking remained unchanged under the specific methodological scenarios tested.

DISCUSSION

Basin level differentiation and the meaning of the SWQI pattern

The application of the proposed SWQI demonstrates a clear differentiation in the physicochemical monitoring signal among the five river basins for which complete six-parameter datasets were available. This differentiation should be interpreted as a comparison of the monitoring stations meeting the complete-case criterion rather than as an unconditional assessment of the overall quality of each basin. Mat recorded the highest basin level SWQI (98.79), followed by Drin-Bunë (97.40), Shkumbin (94.29), and Seman (93.33), whereas Ishëm-Erzen recorded a substantially lower value of 68.54. Under the proposed interpretative thresholds, the first four basins were classified as Excellent and Ishëm-Erzen as Moderate.

The significance of this result is not that the SWQI establishes a new regulatory ecological status classification or provides a spatially exhaustive estimate of basin-wide water quality. Rather, it provides a continuous and directly comparable representation of the physicochemical monitoring signal captured by the included stations within each basin reporting unit. This distinction is important because the basin-level index is based on equal weighting of monitoring stations and does not account explicitly for differences in river

length, discharge, basin area, water-body size, population, or spatial representativeness. The resulting basin-level SWQI should therefore be interpreted as a monitoring-network-based comparative indicator rather than as a spatially weighted estimate of the condition of the entire basin. This is particularly useful where monitoring observations are available at individual stations but the spatial organization of the monitoring information is not yet uniformly aligned with WFD water body delineation. The index therefore provides an intermediate analytical layer between individual observations and basin level interpretation.

Considerable within basin variability, particularly in Seman and Ishëm-Erzen, also demonstrates that basin level aggregation should be interpreted together with station level results. The SWQI therefore provides a summary of the monitored physicochemical signal rather than a substitute for station level diagnosis. This distinction is important for management applications. A high basin level SWQI does not necessarily mean that all monitoring locations or all parameters are performing well, while a lower basin level score provides a signal that warrants examination of the underlying station and parameter level observations. In this respect, the principal value of the SWQI lies in its ability to support screening, comparison and prioritisation, while preserving the underlying monitoring data for more detailed assessment.

Parameter level contributions and within basin variability

The parameter level results provide important context for interpreting the basin level index. DO, NO₂ and NO₃ generally produced the highest normalized scores, while BOD₅ and NH₄ represented the principal downward influences on the composite index. P-total showed an intermediate contribution overall but produced substantially lower scores at selected monitoring stations.

This pattern demonstrates one of the advantages of retaining the parameter level information alongside the composite score. A single SWQI value cannot identify which water quality dimensions are responsible for a relatively low or high score. The combination of parameter level normalized scores and the composite index, however, makes it possible to distinguish between basins with generally favourable conditions and basins in which the overall result is affected by particular parameters or localized observations.

The particularly pronounced within basin variability observed for Ishëm-Erzen is therefore important. The difference between its highest and lowest scoring stations exceeds 60 SWQI points, while Seman also contains stations with substantially lower scores despite its high basin level average. These findings indicate that spatial heterogeneity is an important feature of the monitoring data and that basin level averaging should not be interpreted as evidence of spatial uniformity.

This also reinforces the methodological decision to retain continuous normalized scores rather than replacing the individual observations with categorical classes before aggregation. Continuous normalization preserves differences between observations within and beyond the reference classes and allows those differences to contribute proportionally to the final index.

Why does Ishëm-Erzen produce a substantially lower SWQI?

Its SWQI of 68.54 is approximately 25 points below Seman, the next-lowest basin, and its fifth-ranked position remained unchanged across all tested weighting, aggregation and normalization scenarios, although the absolute SWQI value was sensitive to the methodological configuration.

The importance of Ishëm-Erzen is therefore not simply its lower absolute value. It is the consistency of its relative position. Under alternative weighting configurations, its SWQI varied from 62.05 to 72.46, but it remained the fifth ranked basin in every scenario. Similarly, alternative aggregation methods produced larger changes in the absolute value of the index, particularly for Ishëm-Erzen under less compensatory approaches, but did not change the basin ranking.

This indicates that the relative position of Ishëm-Erzen was not altered by the specific methodological scenarios examined. The result is consistent with a broader pattern present across the monitored parameters and stations.

Importantly, the present dataset does not provide a sufficient basis for attributing this pattern to a particular pressure source. The SWQI identifies a lower physicochemical water quality signal, but identifying the causes of that deterioration would require integration with pressure information, land use data, discharge information, hydro-morphological characteristics and other relevant environmental datasets.

This is an important distinction for the interpretation of the index: SWQI is diagnostic at the level of water quality condition, but not by itself a pressure attribution tool. Gjeçi et al. (2025b) provides contextual information on water quality conditions in the Erzeni–Ishmi system based on NEA/AKM monitoring data collected during 2021–2024. Because the underlying monitoring network and data source may overlap with those used in the present study, this study is not treated as an independent validation source. Differences in study period, parameter selection and assessment methodology nevertheless provide useful context for interpreting the observed spatial variability.

Why Seman differs from the 2025 NEA/RGJM assessment?

The comparison with the 2025 NEA/RGJM assessment provides an important contextual perspective on the SWQI results. The basin level SWQI identified Seman as the second highest quality basin, with a score of 93.33, corresponding to the “Excellent” category under the proposed SWQI classification. This result differs from the national assessment, which indicates less favourable conditions for parts of the Seman system (National Environment Agency, 2025).

The comparison with the national assessment should not be interpreted as formal validation of the SWQI, because the two approaches address related but conceptually different assessment objectives. Rather, the comparison provides an external diagnostic check of whether the basin level signal identified by the SWQI is broadly consistent with, or meaningfully different from, the national regulatory assessment. The observed difference for Seman is therefore interpreted as evidence of the influence of aggregation and compensation within the composite index rather than as evidence that one assessment is intrinsically more correct than the other.

The relatively high Seman SWQI can be explained partly by the compensatory nature of the arithmetic aggregation used in the primary formulation. High normalized scores for several parameters and monitoring stations can offset lower scores for individual parameters or locations. Consequently, a basin may obtain a high overall SWQI even when localized exceedances or poorer individual observations are present. This illustrates an important distinction between a composite index designed to summarize continuous

physicochemical conditions and a regulatory assessment framework that may apply different classification rules and assessment elements.

Gjeçi et al. (2025a) provides contextual information on water quality variability within the Seman Basin based on NEA/AKM monitoring data from 2020–2024. Because the data source and monitoring network may overlap with those used in the present study, these results are not treated as independent validation. Differences in study period, parameter selection, index formulation and aggregation approach provide contextual information for interpreting the present basin-level results.

The SWQI should therefore be interpreted as a complementary quantitative indicator of physicochemical water quality rather than as an alternative to the national ecological status assessment.

Compensatory versus non compensatory aggregation

The aggregation sensitivity analysis provides further insight into the behaviour of the SWQI. The final index uses arithmetic aggregation, which permits compensation between relatively high and low parameter scores. Alternative geometric, harmonic and minimum/non-compensatory approaches were therefore tested specifically to determine whether the basin ranking depended on the degree of compensation permitted between parameters (Dobbie and Dail, 2013; OECD et al., 2008).

The alternative approaches produced increasingly lower absolute SWQI values as the degree of compensation was reduced, particularly for Ishëm-Erzen. Its basin-level SWQI decreased from 68.54 under arithmetic aggregation to 51.15 under geometric aggregation, 36.72 under harmonic aggregation and 23.53 under minimum aggregation. Nevertheless, all four aggregation methods produced the same basin ranking: Mat > Drin-Bunë > Shkumbin > Seman > Ishëm-Erzen.

This result indicates that the principal spatial differentiation observed in the study is not simply a consequence of choosing arithmetic aggregation, although the absolute magnitude and interpretation of the composite score are clearly aggregation dependent. The minimum/non-compensatory approach is particularly conservative because the lowest parameter score at each station determines the station-level result, preventing compensation among parameters at that stage.

The choice of arithmetic aggregation in the final SWQI was therefore made to provide an

integrated measure of the overall physicochemical monitoring signal rather than to reproduce a worst-parameter regulatory classification. The aggregation sensitivity analysis nevertheless shows that the principal basin ordering was preserved under the less compensatory formulations tested.

This distinction is well recognized in the composite indicator literature (Dobbie and Dail, 2013; OECD et al., 2008).

Implications for WFD implementation and the evolving water body framework

The findings have particular relevance for Albania because the national monitoring structure and WFD oriented spatial delineation are not yet uniformly aligned across all monitoring stations included in the analysis (European Commission, 2003; European Parliament & Council, 2000).

The present study deliberately does not infer Water Body IDs where an unambiguous linkage to a formally delineated surface water body is unavailable. Consequently, the SWQI operates on the monitoring station river basin reporting unit structure supported by the available national dataset rather than imposing a retrospective WFD water body structure.

Rather, it reflects the practical situation in which environmental monitoring systems can contain valuable observations before the complete harmonisation of all monitoring locations with WFD water body delineation. In this context, the SWQI can serve as an intermediate analytical framework. It allows existing monitoring information to be quantitatively integrated while the spatial architecture required for full WFD implementation continues to develop.

Once Water Body IDs become consistently available and linked to monitoring stations, the methodology can be extended without fundamentally changing its mathematical structure. The station level SWQI could be aggregated by formally delineated water body and subsequently related to river basin management units.

Transferability to EU candidate countries

The methodological implications extend beyond Albania. Many countries progressing towards EU accession face the challenge of aligning existing national monitoring systems with the spatial, methodological and reporting requirements associated with the WFD.

The proposed framework offers a potentially transferable approach because it does not require complete spatial harmonisation as a prerequisite for the initial integration of monitoring information. It can operate with station based observations, provided that the observations are sufficiently complete and traceable, while allowing the spatial framework to evolve as water body delineation becomes more comprehensive.

The transferability of the approach should nevertheless be understood as methodological rather than regulatory. The SWQI does not provide a substitute for WFD ecological status assessment, and its parameter set, reference boundaries and interpretation thresholds would need to be adapted to the national regulatory and environmental context of another candidate country.

Its potential value lies instead in providing a structured pathway for transforming fragmented or differently organized monitoring information into a transparent composite signal that can support basin level comparison and prioritisation. In this sense, the Albanian case provides a practical example of how a composite indicator can function as a bridge between existing monitoring infrastructure and progressively harmonised WFD oriented assessment systems.

Limitations and future development

Several limitations should be considered when interpreting the results.

First, the quantitative assessment used a complete-case selection criterion, whereby only monitoring stations with numerical observations for all six selected parameters were included. Although this approach ensures that the same six-parameter SWQI is calculated consistently across all included stations and avoids introducing imputed values, it may introduce selection bias if monitoring completeness is systematically related to basin, station characteristics or water-quality conditions. The available source dataset did not provide a sufficiently consistent basis for a formal statistical comparison of included and excluded stations across all six parameters. Consequently, the potential effect of monitoring completeness on spatial representativeness cannot be fully quantified in the present study. Vjosa provides the clearest example, as numerical observations for NO₂, NO₃ and P-total required for the six-parameter calculation were not available in the source material. The basin-level results should therefore be interpreted

as assessments of the complete-case monitoring subset rather than as unconditional estimates of water quality throughout each basin. Future applications should explicitly assess monitoring completeness and, where sufficient data become available, compare complete and incomplete monitoring subsets or apply appropriately justified missing-data approaches.

Second, the basin-level SWQI uses equal weighting of monitoring stations, while the number and spatial distribution of stations differ among basins. Ishëm-Erzen is represented by 10 stations, Seman by 8, Drin-Bunë by 7, and Mat and Shkumbin by 4 each. Equal station weighting was selected because consistent information on river length, discharge, basin area, water-body size and other spatial or hydrological weighting variables was not available for all stations in a form that could be applied uniformly. This approach avoids introducing unsupported weighting assumptions, but it also means that the basin-level SWQI is influenced by monitoring-network density and spatial coverage. The resulting index therefore characterizes the physicochemical monitoring signal represented by the included stations rather than providing a spatially exhaustive estimate of basin-wide water quality. This potential network-related bias should be considered when comparing basins with different monitoring densities. Future applications should investigate spatially or hydrologically informed aggregation, particularly as monitoring stations become more consistently linked to formally delineated WFD surface water bodies.

Third, the analysis is based on the available monitoring observations and therefore represents the conditions captured by the monitoring network rather than a complete spatial representation of all surface waters within each basin. The relatively large within basin variability observed in Seman and Ishëm-Erzen illustrates why monitoring network density and spatial representativeness remain important considerations.

Fourth, the present SWQI is restricted to six physicochemical parameters. It therefore does not incorporate biological quality elements, hydro-morphological elements or all river basin specific pollutants relevant to the broader WFD ecological status framework. The SWQI should consequently not be interpreted as an ecological status index.

Five, the 90/70/50/25 interpretation thresholds are proposed SWQI categories, developed specifically to facilitate interpretation of the composite score. They are not direct equivalents of

the national physicochemical classes or WFD ecological status classes. The sensitivity testing nevertheless showed that alternative threshold configurations did not alter the qualitative classification of the five quantitatively assessed basins.

CONCLUSIONS

This study adapted and applied a composite SWQI framework to assess and compare the physicochemical monitoring signal represented by monitoring stations across Albanian river basin reporting units using six physicochemical parameters: DO, BOD₅, NH₄, NO₂, NO₃, and total phosphorus (P-total). The assessment was based on monitoring data from 33 stations distributed across five river basins with complete six parameter datasets. A bounded continuous normalization approach was applied to retain information from observations exceeding Class V conditions while constraining the resulting scores to the 0–100 scale.

The results showed descriptive differentiation in the monitoring-network-based SWQI among the assessed basin reporting units. Mat recorded the highest basin level SWQI (98.79), followed by Drin-Bunë (97.40), Shkumbin (94.29), and Seman (93.33), while Ishëm-Erzen recorded the lowest value (68.54). Under the proposed SWQI classification, the first four basins were classified as Excellent, whereas Ishëm-Erzen was classified as Moderate. The station level results also demonstrated considerable within basin variability, particularly in Ishëm-Erzen and Seman, showing that basin level aggregation can mask important spatial differences between monitoring locations.

The parameter level assessment showed that DO, NO₂ and NO₃ generally contributed the highest normalized scores, whereas BOD₅ and NH₄ represented the principal downward influences on the composite index. P-total showed an intermediate contribution but generated substantially lower scores at selected stations. These results demonstrate the importance of interpreting the composite SWQI together with the underlying parameter level results, particularly where individual parameters indicate localized poorer water quality conditions.

The sensitivity analysis showed that the principal basin-level ranking remained unchanged under the specific weighting, aggregation and normalization scenarios examined, although absolute SWQI values varied under some methodological choices.

Comparison with the 2025 NEA/RGJM assessment demonstrated that the SWQI should be interpreted as a complementary assessment tool rather than a replacement for the national regulatory classification framework. Differences between the two approaches, particularly for Seman, highlight the influence of parameter selection, aggregation and the compensatory nature of composite indices. The comparison was used as an external consistency assessment rather than as formal validation, because the SWQI and the national regulatory assessment are based on different assessment frameworks and are not intended to represent identical constructs. The SWQI is therefore most appropriately used alongside individual parameter results and the national regulatory assessment to support interpretation of water quality conditions.

Acknowledgements

The authors acknowledge the financial support provided by the National Agency for Scientific Research and Innovation (NASRI), Albania, for the preparation of this article within the framework of the project entitled “Technical and Engineering Assessment and Analysis of Wastewater Treatment Plants in Albania”, approved by Decision No. 5, dated 30 April 2025, of the Board of Administration of the National Agency for Scientific Research and Innovation (NASRI), Ministry of Education and Sports, Albania.

REFERENCES

1. Brown, R. M., McClelland, N. I., Deininger, R. A., Tozer, R. G. (1970). A water quality index—Do we dare? *Water & Sewage Works*, 117(10), 339–343.
2. Council of Ministers of the Republic of Albania. (2023). *River basin management plans for the Ishëm and Erzen river basins, 2024–2029*. Tirana, Albania.
3. Council of Ministers of the Republic of Albania. (2025). Decision No. 636, dated 5 November 2025, on the determination of the hydrographic and territorial boundaries of river basins and river basin regions, other surface water bodies, groundwaters and coastal waters. Tirana, Albania.
4. Dobbie, M. J., Dail, D. (2013). Robustness and sensitivity of weighting and aggregation in constructing composite indices. *Ecological Indicators*, 29, 270–277. <https://doi.org/10.1016/j.ecolind.2012.12.025>
5. European Commission. (2003). *Guidance document No. 2: Identification of water bodies. Common Implementation Strategy for the Water Framework Directive (2000/60/EC)*. European Communities.
6. European Parliament & Council of the European Union. (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities*, L327, 1–73.
7. Gjeçi, V., Qarri, F., Lazo, P. (2025a). Assessment of the Seman basin water quality, Albania, based on physical-chemical parameters during 2020–2024. *Journal of Natural Sciences*, 37, 16–40. <https://doi.org/10.70827/aotsw>
8. Gjeçi, V., Shehu Kane, S., Lazo, P., Paparisto, A., Kecia, K. (2025b). Assessment of water quality of Erzeni-Ishmi basin, Albania. *Chemistry and Ecology*, 41(10), 1303–1322. <https://doi.org/10.1080/02757540.2025.2529928>
9. Lumb, A., Halliwell, D., Sharma, T. (2006). Application of CCME water quality index to monitor water quality: A case study of the Mackenzie River basin, Canada. *Environmental Monitoring and Assessment*, 113(1–3), 411–429. <https://doi.org/10.1007/s10661-005-9092-6>
10. National Environment Agency (AKM). (2025). *Environmental status report 2025*. Tirana, Albania. https://akm.gov.al/ova_doc/raporti-per-gjendjen-e-mjedisit-2025-3/
11. OECD, European Union, EC-JRC. (2008). *Handbook on constructing composite indicators: Methodology and user guide*. OECD Publishing. <https://doi.org/10.1787/9789264043466-en>
12. Pesce, S. F., Wunderlin, D. A. (2000). Use of water quality indices to verify the impact of Córdoba City (Argentina) on Suquia River. *Water Research*, 34(11), 2915–2926. [https://doi.org/10.1016/S0043-1354\(00\)00036-1](https://doi.org/10.1016/S0043-1354(00)00036-1)
13. Sargaonkar, A., Deshpande, V. (2003). Development of an overall index of pollution for surface water based on a general classification scheme in Indian context. *Environmental Monitoring and Assessment*, 89(1), 43–67. <https://doi.org/10.1023/A:1025886025137>
14. Smith, D. G. (1989). A new form of water quality index for rivers and streams. *Water Science and Technology*, 21(2), 123–128. <https://doi.org/10.2166/wst.1989.0038>
15. State Authority for Geospatial Information (ASIG). (2025). *Ecological status—Surface water bodies: Ishëm and Erzen river basins*. National Geoportal, Albania.
16. Sutadian, A. D., Muttill, N., Yilmaz, A. G., Perera, B. J. C. (2016). Development of river water quality indices—A review. *Environmental Monitoring and Assessment*, 188(1), 58. <https://doi.org/10.1007/s10661-015-5050-0>
17. Uddin, M. G., Nash, S., Olbert, A. I. (2021). A review of water quality index models and their use for assessing surface water quality. *Ecological Indicators*, 122, 107218. <https://doi.org/10.1016/j.ecolind.2020.107218>