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Alexandra Ioannou
University of Thessaly
Nikolaos Kokosis
University of Thessaly
Evmorfia Bataka
University of Thessaly
Charalambos Billinis
University of Thessaly
Chrysi Laspidou
laspidou@uth.gr

University of Thessaly

Article

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Posted Date: November 18th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11140237/v1

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Additional Declarations: No competing interests reported.

Operationalising a proxy-based coastal One Health indicator under data constraints: weighting robustness and sensitivity in the Pagasitikos Gulf, Greece

Authors

Alexandra Ioannou [1,] ORCID: https://orcid.org/0000-0001-5818-9836

Nikolaos Kokosis [1,2], ORCID: https://orcid.org/0009-0005-9515-062X

Evmorfia Bataka[1,] ORCID: https://orcid.org/0000-0003-1631-1949

Charalambos Billinis[3,] ORCID: https://orcid.org/0000-0002-2209-9772

and Chrysi Laspidou[1,] * ORCID: https://orcid.org/0000-0001-5225-4844

[1] Department of Civil Engineering, University of Thessaly, 38334 Volos, Greece

[2] Department of Planning and Regional Development, University of Thessaly, 38334 Volos, Greece

[3] Faculty of Veterinary Medicine, University of Thessaly, 43100 Karditsa, Greece

[*] Corresponding author: laspidou@uth.gr

Abstract

Operational coastal One Health metrics remain scarce where direct health outcomes are unavailable. We developed a proxy-based hierarchical composite One Health Indicator (OHI) for the Pagasitikos Gulf, Greece, as an operational adaptation of a published framework. The 40-month implementation (January 2023–April 2026) integrates Copernicus satellite-observation, blended-observation and marine-model products with local monitoring and administrative records in three branches: a human-exposure proxy (HHI), an Aquatic Animal Health Index retained as an operational label and interpreted as an aquatic habitat-condition proxy (AAHI), and an Environmental Health Index (EHI) containing a nested operational Water Quality Index. Equal and expert-informed intensity weights were compared in 1,000 matched Sobol-sequence quasi-Monte Carlo runs that perturbed 21 normalised score contributions using Uniform (0.9, 1.1) marginals. In April 2026, nominal OHI values were 53.69 and 51.91 under expert-informed and equal weighting; simulation means were 53.55 and 51.80, with conditional 2.5th–97.5th percentile intervals of 51.74–55.29 and 50.00–53.58. The matched difference averaged 1.76 points and was positive in all runs. Dissolved oxygen, chlorophyll-a and pH had the largest absolute SRCs at the April 2026 step. The indicator is an auditable screening synthesis, not a validated measure of human or animal health.

Keywords: One Health; composite indicator; coastal monitoring; Copernicus Marine; quasi-Monte Carlo; sensitivity analysis.

1. Introduction

One Health (OH) is an integrated, unifying approach intended to sustainably balance and optimise the health of people, animals and ecosystems by recognising their interdependence [1]. Its contemporary scope extends beyond zoonotic disease and antimicrobial resistance to environmental change, biodiversity loss, food and water security, and preparedness for health crises [1]. This broadened mandate is especially relevant to coastal systems, where ecological condition, aquatic organisms and human exposure pathways intersect. Nevertheless, the conceptual expansion of OH has not yet been matched by equally mature operational metrics. Coastal and marine OH research remains dispersed across disciplines, data types and endpoints, and relatively few studies translate the three-domain concept into repeatable quantitative assessments that can be scrutinised by managers and scientists [2]. Even before direct outcome data are available, a transparent screening architecture can provide a reproducible baseline for harmonising heterogeneous observations, comparing modelling assumptions and identifying the epidemiological, toxicological and aquatic-animal data required for prospective validation. It can therefore support staged

replication and improvement across coastal systems without being interpreted as a validated health-status instrument.

Coastal waters provide food, livelihoods, recreation, cultural value and protection while receiving land-based pressures from catchments and settlements. The relationship is bidirectional: society modifies ocean conditions through development, runoff, resource use and pollution, whereas altered ocean conditions can affect wellbeing, seafood safety and the health of wild or farmed aquatic organisms [3]. Nutrient enrichment, harmful algal blooms, microbial contamination, suspended sediments, warming, acid–base changes and oxygen depletion may occur concurrently and at different scales. Because these processes are usually monitored in separate sectoral programmes, an observed change may be difficult to interpret as an isolated water-quality issue or as part of a broader OH concern.

Extreme hydroclimatic events make land–sea interdependencies particularly visible. Floods can transport freshwater, sediment, nutrients, sewage-associated material and agricultural or industrial contaminants into receiving waters. Storm Daniel produced exceptional rainfall and flooding in Thessaly during 4–7 September 2023 [4]. Subsequent chemical screening documented pollution pathways and emerging contaminants in affected Thessalian coastal waters [5]. These findings motivate integrated coastal observation, but they do not by themselves validate a health index or establish that changes in a monthly composite were caused by the event. A defensible event-effect analysis would require predefined pre-event and post-event windows, seasonal controls or a counterfactual, and independent outcome data.

Copernicus Marine observation- and model-based products can help characterise heterogeneous coastal conditions by providing spatially and temporally consistent physical, optical and biogeochemical fields [6]. Quantities such as chlorophyll-a, turbidity, sea-surface temperature, salinity, dissolved oxygen and pH are nevertheless environmental state or pressure variables; they do not directly measure infection, toxicological dose, fish pathology or population health. Composite indices can integrate such evidence, as demonstrated at a broader scale by the Ocean Health Index [7], but their interpretation depends on whether the underlying variables genuinely represent the intended constructs.

Composite-indicator construction embeds choices about variable selection, missing-data treatment, normalisation, directionality, weighting and aggregation [8]. Equal weighting is transparent but not assumption-free; expert-informed weighting can encode contextual judgement but requires a reproducible elicitation record. Additive aggregation permits compensation, and repeated use of the same environmental variable in several branches can increase its effective influence. Uncertainty and sensitivity analysis are therefore important for examining numerical robustness [9,10]. However, the interpretation of a sensitivity measure must match the perturbed quantity: varying an already-normalised score contribution tests the conditional behaviour of that contribution, not uncertainty in the original environmental measurement.

Here we developed a data-constrained operational adaptation of the coastal OH framework proposed by Ioannou et al. [11] for the Pagasitikos Gulf, a semi-enclosed Mediterranean embayment of ecological and fishery importance [12]. The published framework defines the Human Health Outcome Index (HHOI), Aquatic Animal Health Risk Index (AAHRI) and Environmental Ecosystem Quality Index (EEQI). The ENHANCE Stella prototype instead uses the shorter implementation labels HHI, AAHI and EHI; these operational branches map to, but do not reproduce the full outcome- and risk-based content of, the three published domains. The present study contributes a first 40-month implementation, a matched comparison of two fixed weighting scenarios, an effective-weight audit and an independently auditable conditional score-contribution uncertainty and sensitivity experiment. It is intended as a transferable baseline for progressive extension with direct epidemiological, toxicological and aquatic-animal outcome data. The study period spans January 2023–April 2026 and includes Storm Daniel as contextual motivation rather than as a causal pre/post design. We asked: (i) can heterogeneous observations be harmonised into a transparent, sample-relative screening signal; (ii) how much do equal and expert-informed within-branch weights alter the temporal trajectory and April 2026 value when evaluated with identical perturbations; and (iii) which already-normalised contributions show the largest conditional responses under the specified experiment? The framework provides an auditable and transferable basis for integrating heterogeneous coastal observations, comparing alternative weighting schemes and progressively incorporating direct human-, animal- and ecosystem-health evidence.

2. Methods

2.1 Study area and analytical design

The study focused on the Pagasitikos Gulf in central Greece, a semi-enclosed coastal system connected to the Aegean Sea through the Trikeri Channel. The Gulf is bordered by Volos to the north and the Pelion peninsula to the east; its wider catchment is influenced by urban activity, agriculture, fisheries and tourism [12]. The analysis was conducted at the gulf case-study scale and was not designed for individual- or station-level exposure inference.

The location and spatial extent of the Pagasitikos Gulf case study, including its relationship to Volos and the wider regional setting, are shown in Fig. 1.



Figure 1**.** Location of the Municipality of Volos and Pagasitikos Gulf case-study areas within the Magnesia Regional Unit, Greece. Map produced by the authors using ELSTAT 2021 administrative-boundary data and Copernicus DEM GLO-30 elevation data.

The analysis-ready matrix comprised 40 monthly records from January 2023 through April 2026. Storm Daniel (4–7 September 2023) falls within this period [4], and related post-event chemical screening provides contextual evidence of coastal pollution pathways [5]. No prospectively defined event window, seasonally matched baseline or counterfactual was used; consequently, temporal results are descriptive and are not interpreted as an estimate of flood impact.

The workflow translated the coastal OH hierarchy of Ioannou et al. [11] into a composite coastal One Health Indicator, reported using the Stella model output label OHI, through six steps: assembly of Copernicus observation and marine-model products with local monitoring and administrative variables; deterministic completion of missing values; directionally harmonised sample-relative scoring; definition of equal and expert-informed weighting scenarios; hierarchical aggregation into branch and overall indices;

and a matched conditional contribution uncertainty and sensitivity experiment. HHI, AAHI and EHI are operational implementation labels rather than the formal HHOI, AAHRI and EEQI names of the published conceptual framework. Here, HHI is interpreted as a human-exposure proxy, while AAHI is retained as the operational Aquatic Animal Health Index label but interpreted strictly as an aquatic habitat-condition proxy because its seven constituents—DO, turbidity, pH, SSS, chlorophyll-a, current velocity and OMLT—are exclusively environmental variables. No direct epidemiological, biological, pathological or veterinary outcome data were available. Neither HHI nor AAHI should therefore be interpreted as a direct health-outcome measure.

2.2 Indicator evidence base

The evidence base combined Copernicus Marine gridded products with local administrative and monitoring variables. No raw satellite scenes were processed. Copernicus data were requested through MyOcean Pro for 39.087713–39.371566° N, 22.743383–23.229404° E and January 2023–April 2026 [13–16]. Chlorophyll-a and sea-water turbidity came from the Sentinel-2-based daily Level-3 Mediterranean high-resolution ocean-colour product at 100 m (OCEANCOLOUR_MED_BGC_HR_L3_NRT_009_205; DOI: 10.48670/moi-00109) [13]. Sea-water currents at 1.02 m and ocean mixed-layer thickness came from the Mediterranean Sea Physics Analysis and Forecast numerical-model product at approximately 4 km (MEDSEA_ANALYSISFORECAST_PHY_006_013; DOI: 10.48670/mds-00359) [14]. Dissolved molecular oxygen, pH, nitrate and phosphate came from the Mediterranean Sea Biogeochemistry Analysis and Forecast numerical-model product at approximately 4 km (MEDSEA_ANALYSISFORECAST_BGC_006_014; DOI: 10.48670/mds-00358) [15]; nitrate and phosphate corresponded to NetCDF variables no3 and po4 in mmol m^{-3}, but the exact vertical level and temporal nutrient subdataset were not retained. Sea-surface salinity came from a blended multi-observation Level-4 product at 0.125° (MULTIOBS_GLO_PHY_S_SURFACE_MYNRT_015_013; DOI: 10.48670/moi-00051) [16]. Sea-surface temperature was obtained through MyOcean Pro and retained in kelvin, but the exact upstream product and subdataset were not preserved. The currently identifiable catalogue records for the biogeochemistry and physics products begin in October and November 2023, respectively. Early-study months were represented as missing where the supplied matrix contained blanks. The OMLT series was complete in the supplied matrix, but the archived workflow does not preserve whether its January–October 2023 values came from an earlier product version or a prior extraction; those months could not be reconstructed upstream.

The downloaded NetCDF-4 files were imported into R, spatially subset to the defined domain, restricted to the study period and aggregated to calendar-month gulf-level means across all available valid water pixels. The resulting monthly tables were exported to a Microsoft Excel workbook (.xlsx) and incorporated into the analysis-ready input matrix used for indicator calculation.

The 21 model input terms were dissolved oxygen (DO), turbidity, pH, sea-surface temperature (SST), sea-surface salinity (SSS), chlorophyll-a, absolute current velocity, ocean mixed-layer thickness (OMLT), total precipitation, Escherichia coli, intestinal enterococci, nitrate (NO3), phosphate (PO4), total nitrogen (TN), total phosphorus (TP), biochemical oxygen demand (BOD5), chemical oxygen demand (COD), total suspended solids (TSS), ammonium nitrogen (NH4-N), riverine influence (RIV; legacy analysis-ready field: RPI; Stella model label: Riverine influence) and an employment-flow density proxy. Their hierarchy positions, source-field labels, missingness summaries, empirical normalisation anchors and within-parent weights are reported in Supplementary Table S1.

Six local series (BOD5, COD, TSS, TP, NH4-N and TN) were retained from the supplied operational model files. The available archive links these series to DEYAMB and the Hellenic Ministry of Environment and Energy's Wastewater Treatment Plants Monitoring Database [17], but does not preserve the monitoring point, sampling matrix (ambient coastal water, treatment-plant influent or effluent), analytical method or independently verified unit. They were therefore used only as legacy wastewater-related pressure inputs within the operational sub-index labelled WQI and must not be interpreted as ambient concentrations in the Pagasitikos Gulf. Their inclusion reproduces the existing Stella implementation rather than independently validating the environmental meaning of those series. The close numerical correspondence between TN and TSS during the first 24 months was retained because it occurs in the archived source-derived series; it remains a potential source-data limitation and is not interpreted as environmental equivalence.

The DEYAMB-linked information was represented at two analytical levels in the operational hierarchy. The six constituent series entered EHI through the nested WQI as parameter-level pressure indicators, while RIV summarised their joint temporal signal as an aggregate pathway-level proxy within HHI. This

shared-source representation preserves the original model architecture and should not be interpreted as an independent evidence stream.

The employment-flow density proxy was calculated as the ERGANI monthly balance of hires minus exits for the Regional Unit of Magnesia divided by a fixed Volos industrial-zone area of 3.34537644 km² and was expressed as jobs km^{-2}. Negative balances were permissible. It is an administrative labour-market proxy retained from the operational model, not a direct measure of industrial production, emissions or coastal exposure. Thirty-six monthly values covered January 2023–December 2025; January–April 2026 were completed using the same-calendar-month median rule described in Section 2.3.

Product-level identifiers, DOIs, variable names, units, study bounds, nominal spatial resolutions and the monthly gulf-level aggregation rule are reported for Copernicus-derived series where verified. The exact upstream SST product and subdataset, the selected vertical level and temporal subdataset for NO3 and PO4, file-level versions, retrieval timestamps and monthly valid-pixel counts were not preserved. The shared DEYAMB source family underlying RIV was identifiable, although the archived files did not preserve its complete derivation metadata or an independently verified unit. Local records lacked some sampling-matrix, unit and laboratory-method metadata. These provenance gaps do not alter calculations performed on the supplied matrix, but they limit exact upstream reconstruction and interpretation. Spatial averaging at gulf scale further combines products with markedly different native resolutions and may obscure nearshore hotspots. Because the constituent variables represent environmental state, pressure and exposure-related evidence rather than clinical, epidemiological, biological or veterinary outcomes, HHI is interpreted as a human-exposure proxy and AAHI as an aquatic habitat-condition proxy rather than as direct measures of health.

2.3 Treatment of missing predictor values

Before scoring, missing values were replaced using a deterministic month-to-season-to-global median hierarchy calculated from originally observed values only [18–20]. An available audit covered 20 variables and recorded 216 imputed cells among 800 variable-month cells (27.0%); TN was not included in that audit, so its missing-data provenance could not be independently verified. The completed 21-variable analysis matrix contained no blanks.

For continuous, signed or narrow-range variables, values were imputed on the native scale using the median of observations from the same calendar month. If no same-month reference existed, a seasonal median was used, followed by a global median if required. Seasons were winter (December–February), spring (March–May), summer (June–August) and autumn (September–November). With only 40 months, same-month reference sets were necessarily small, so this procedure preserves calendar structure only approximately.

For non-negative, skew-prone or episodic variables, the transformation in equation (1) was applied before selecting the relevant median.

$$z_t = \ln \quad (1 + x_t) \tag{1}$$

If $\tilde{z}_t$ denotes the selected transformed-scale median, the completed value was returned to the original scale using equation (2).

$$\hat{x}_t = \exp \quad (\tilde{z}_t) - 1 \tag{2}$$

This rule was applied to E. coli, enterococci, BOD5, COD, TSS, TP, NH4-N, NO3, PO4, precipitation and riverine influence. Robustness to episodic extremes comes principally from the median; because log1p is monotonic, it preserves an odd-sample median after back-transformation and can differ only for even reference sets because their two central transformed values are averaged.

Observed values alone defined every reference set; an imputed value was never reused to fill another cell, and no downstream index value entered the procedure. The supplied audit records variable-level counts and fallback categories, but row-level observed/imputed flags were not available in the files reviewed for this revision.

Missingness was consequential for several variables: E. coli and enterococci were each imputed in 23/40 months (57.5%); BOD5, COD, TSS, TP, NH4-N, precipitation and riverine influence were each imputed in 16/40 months (40.0%); pH in 12/40 months (30.0%); current velocity in 11/40 months (27.5%); and DO, NO3 and PO4 in 10/40 months (25.0%). Deterministic single imputation does not propagate uncertainty in these values, and results involving heavily completed variables require particular caution.

2.4 Normalisation and directionality harmonisation

Each completed series was transformed to 0–100 using full-period empirical anchors. The 5th and 95th percentiles in equation (3) were calculated with linear interpolation equivalent to R quantile type 7. The same January 2023–April 2026 anchors were used for every month; they are sample-relative scaling statistics, not regulatory, toxicological or ecological thresholds [8,9]. With n=40 and type-7 interpolation, P05 lies between the second and third ordered observations and P95 between the 38th and 39th. Both anchors can therefore shift materially if one or two atypical months change and should be interpreted as pragmatic scaling anchors rather than stable estimates of the distributional tails.

$$\mathrm{P05}_j = Q_{0.05}(X_j), \qquad \mathrm{P95}_j = Q_{0.95}(X_j) \tag{3}$$

Each observation was clipped to [$P05_j$, $P95_j$] using equation (4). Across 840 variable-month values, 42 fell below P05 and 41 above P95 before clipping (5.00% and 4.88%, respectively). Clipping therefore limits tail leverage but also saturates the empirical extremes.

$$x^*_{t,j} = \min \left\{\max(x_{t,j}, \mathrm{P05}_j), \mathrm{P95}_j\right\} \tag{4}$$

For monotonic benefit variables, the clipped value was mapped with equation (5). DO and the magnitude of current velocity were treated as benefits within this operational scoring model. These direction assignments are modelling assumptions and were not calibrated against variable-specific ecological dose–response functions or regulatory classes.

$$S_{t,j} = 100\,\frac{x^*_{t,j} - \mathrm{P05}_j}{\mathrm{P95}_j - \mathrm{P05}_j} \tag{5}$$

For monotonic pressure variables, direction was reversed using equation (6). This class included turbidity, chlorophyll-a, E. coli, enterococci, BOD5, COD, TSS, TP, NH4-N, NO3, PO4, TN, precipitation, riverine influence and the employment-flow density proxy. Chlorophyll-a was used as a phytoplankton-biomass/eutrophication proxy; it does not identify harmful algal taxa, toxins or bloom occurrence. These operational directions are hypotheses to be validated, not health-protective thresholds.

$$S_{t,j} = 100\,\frac{\mathrm{P95}_j - x^*_{t,j}}{\mathrm{P95}_j - \mathrm{P05}_j} \tag{6}$$

pH, SST, SSS and OMLT were scored as non-monotonic variables around their empirical median. The median M_j and the larger anchor-to-median distance D_j were defined by equation (7).

$$M_j = \mathrm{median}(X_j), \qquad D_j = \max \left\{|\mathrm{P95}_j - M_j|, |M_j - \mathrm{P05}_j|\right\} \tag{7}$$

Equation (8) assigns 100 at the sample median and lower values with increasing departure in either direction. This is a descriptive centre-of-sample rule, not evidence that the median is an ecological optimum; it does not model variable-specific acceptable ranges, asymmetric effects or seasonal climatology. If $P95_j$=$P05_j$, a neutral score of 50 was prespecified; this safeguard was not triggered. Final scoring rules and numerical anchors are reported in Supplementary Table S1.

$$S_{t,j} = \max \left\{0, \min\left[100, 100\left(1 - \frac{|x^*_{t,j} - M_j|}{D_j}\right)\right]\right\} \tag{8}$$

2.5 Weighting scenarios

Two fixed weighting scenarios were compared while holding the input matrix, normalisation rules and hierarchy constant. The benchmark assigned equal effective weights to leaf indicators within each branch. HHI and AAHI used local leaf weights of 1/11 and 1/7, respectively. Within EHI, each of the 14 leaf indicators received an effective weight of 1/14, implemented through eight direct indicators and a nested six-component WQI with a combined EHI weight of 6/14. Equal weighting is transparent but represents a substantive assumption rather than a value-free default [8,9].

The alternative weighting scenario was reconstructed from the supplied AHP report [21]. Leaf components were assigned integer importance intensities on a 1–9 scale; within EHI, the nested WQI branch received the sum of its six leaf intensities (42). For each set of sibling entries, a reciprocal matrix was reconstructed as $a_{ij}=s_i/s_j$, yielding normalised weights equivalent to $w_j=s_j/\Sigma s_j$. The resulting consistency ratio was zero by construction and confirms algebraic ratio consistency, not agreement among experts. The three top-level branches remained equally weighted (1/3 each) in both scenarios. Within the expert-informed EHI, the raw intensities were DO 9, turbidity 8, pH 8, precipitation 6, chlorophyll-a 7, SSS 5, SST 5, employment-flow

density proxy 4 and nested WQI 42 (sum 94). Within WQI, TP, NH4-N and TN received 8 each, whereas COD, TSS and BOD5 received 6 each (sum 42). Normalised within-parent weights are listed in Supplementary Table S1.

The available elicitation record identified three contributing experts but did not retain their disciplines, selection criteria or individual responses, nor any dispersion or consensus statistic. The alternative is therefore described as an expert-informed intensity-weighting scenario reconstructed from an AHP report, not as a validated expert consensus. Weights were treated as fixed; the present analysis compares two specified scenarios and does not quantify elicitation uncertainty.

2.6 Hierarchical aggregation and effective contribution audit

Directionally harmonised scores were combined into HHI, AAHI and the Environmental Health Index (EHI); an operational six-component pressure sub-index labelled Water Quality Index (WQI) was nested within EHI. For each parent k and month t, aggregation followed the weighted arithmetic mean in equation (9).

$$I_{t,k} = \sum_{j=1}^{n_k} w_{j,k} S_{t,j,k}, \qquad \sum_{j=1}^{n_k} w_{j,k} = 1 \tag{9}$$

Here, $I_{t,k}$ is parent index k, $S_{t,j,k}$ is the normalised score of child j and $w_{j,k}$ is its within-parent weight, with weights summing to one. The hierarchical aggregate defines the composite coastal One Health Indicator and retains OHI as the model output label; it was calculated using equation (10).

$$\mathrm{OHI}_t = W_H \mathrm{HHI}_t + W_A \mathrm{AAHI}_t + W_E \mathrm{EHI}_t, \qquad W_H + W_A + W_E = 1 \tag{10}$$

The top-level coefficients W_H, W_A and W_E were 1/3. Because several leaf variables appear in multiple branches, effective OHI-level influence was audited by summing each variable's products of weights along every path. DO, turbidity, pH, SSS and chlorophyll-a are each reused in all three branches and jointly account for 50.8658% of total effective leaf weight under equal weighting and 50.9362% under expert-informed weighting. The three branches therefore represent related screening perspectives, not statistically independent health domains.

A complementary source-family audit was applied to the DEYAMB-linked information represented through the six WQI constituents and the aggregate RIV pathway proxy. This shared information family accounted for 17.32% of effective OHI weight under equal weighting and 18.43% under expert-informed weighting. These values quantify its representation across parameter and pathway levels rather than contributions from independent evidence streams.

Additive aggregation was selected for transparency, but it permits compensation: a high score in one branch can offset a low score elsewhere. Results are consequently reported with pillar-level values and should not be interpreted from OHI alone [8,9].

2.7 Matched quasi-Monte Carlo uncertainty and sensitivity analysis

The matched quasi-Monte Carlo experiment evaluated conditional score-space uncertainty and sensitivity by perturbing already-normalised score contributions. It did not propagate raw measurement error, uncertainty in empirical anchors, imputation uncertainty, environmental dependence or uncertainty in the elicited weights. For run r, score $S_{t,j}$ was multiplied and clipped using equation (11).

$$S_{t,j}^{(r)} = \min\left\{100, \max\left[0, m_j^{(r)} S_{t,j}\right]\right\}, \qquad m_j^{(r)} \sim \mathcal{U}(0.9, 1.1) \tag{11}$$

The 21 dimensions of the Sobol design targeted independent Uniform(0.9, 1.1) marginals; the realised low-discrepancy points were not independent random draws. Within each run, one multiplier was assigned to each encoded model contribution, held constant across all 40 monthly steps and applied to every hierarchy path in which that contribution occurred. Separate dimensions for the disaggregated WQI constituents and the aggregate RIV term were retained to evaluate the local stability of the implemented pathways; they should not be interpreted as evidence of source independence.

The symmetric ±10% range was selected as a common dimensionless stress-test envelope because variable-specific measurement, retrieval and imputation-error models were unavailable. Missingness proportions were not used to widen the ranges because the proportion of deterministically completed values is not an estimate of imputation error. The design therefore supports a like-for-like comparison of normalised

contribution behaviour, not a comparison of total variable-specific uncertainty or confidence. Identical 21-dimensional vectors were supplied to the equal and expert-informed models, enabling matched run-wise differences. The experiment used 1,000 Sobol low-discrepancy points in Stella Architect 3.7 (build 3335), method sobol_sequence. A fixed 1,000-run computational budget was retained so that all analyses correspond to the archived paired dataset; the exact 1,000 × 21 multiplier matrix is provided in Supplementary Data 1 and serves as the computational record. The first retained point set every multiplier to one and represents the nominal configuration. The workflow is summarised in Fig. 2.

The model was evaluated at 40 monthly time steps, with model time 1 corresponding to January 2023 and model time 40 to April 2026. For each output and month, we calculated the nominal value and distributional summaries across runs. The 2.5th–97.5th percentile range is a conditional simulation interval under this perturbation design, not a sampling confidence interval, predictive interval or empirical measurement-uncertainty interval. Expert-minus-Equal differences were calculated within matched runs.

For April 2026, standardised regression coefficients (SRCs) were estimated from multivariable linear metamodels of output on the 21 standardised multipliers. Absolute SRCs were used for ranking; squared SRCs normalised to 100% are descriptive shares, not Sobol variance indices. The multiplier design was effectively orthogonal (maximum absolute pairwise correlation 0.0209; variance-inflation factors 1.0003–1.0011; condition number of the multiplier correlation matrix 1.105). Thus multicollinearity among perturbation inputs was negligible by design, irrespective of correlations among the original environmental series. Standardised rank-regression coefficients and Spearman correlations were secondary checks. Convergence was examined using nested prefixes of 64, 128, 256, 512 and 1,000 points. Because the multipliers act after normalisation in an additive hierarchy, SRCs primarily reflect effective weights, April 2026 score magnitudes and clipping; they are not causal environmental effects or monitoring priorities. April 2026 was selected because it was the final time step of the completed analysis-ready series; it represents a terminal analytical snapshot and is not assumed to be ecologically representative of the full time series.

2.8 Use of AI-assisted tools

ChatGPT (OpenAI) was used during manuscript preparation for language editing, document restructuring, consistency checks and assistance in drafting reproducible figure scripts. It was not used to generate observations or to make autonomous scientific decisions. All outputs were critically reviewed and verified by the authors, who take responsibility for the manuscript.

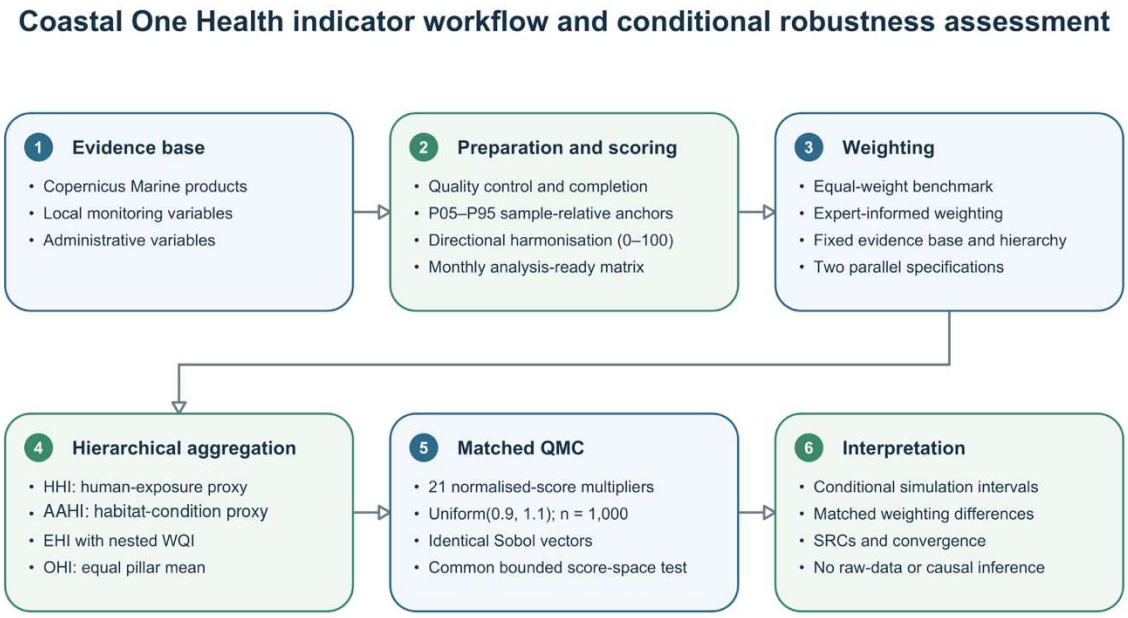


Figure 2. Composite coastal One Health Indicator workflow and matched uncertainty/sensitivity design. The evidence base is completed where necessary and transformed to sample-relative, directionally harmonised 0–100 scores before hierarchical aggregation. Equal and expert-informed within-branch weights are evaluated using matched Sobol-sequence quasi-Monte Carlo inputs. HHI, AAHI and EHI are operational Stella labels mapped to, but not identical with, the HHOI, AAHRI and EEQI domains of the published framework [11]. Here, HHI is a human-exposure proxy and AAHI an aquatic habitat-condition proxy rather than a direct health outcome.

3. Results

3.1 Monthly behaviour and conditional uncertainty

The two weighting scenarios reproduced the same broad monthly pattern from January 2023 through April 2026 (Fig. 3a). Across the 40 months, median OHI ranged from 43.82 to 74.21 under expert-informed weighting and from 45.94 to 72.69 under equal weighting. The mean matched Expert-minus-Equal difference was positive in 24 months and ranged from −2.61 to +1.76 points (Fig. 3b). The vertical marker identifies September 2023, but no discontinuity or flood effect is estimated; the higher expert-informed value in April 2026 is not a time-invariant ordering.

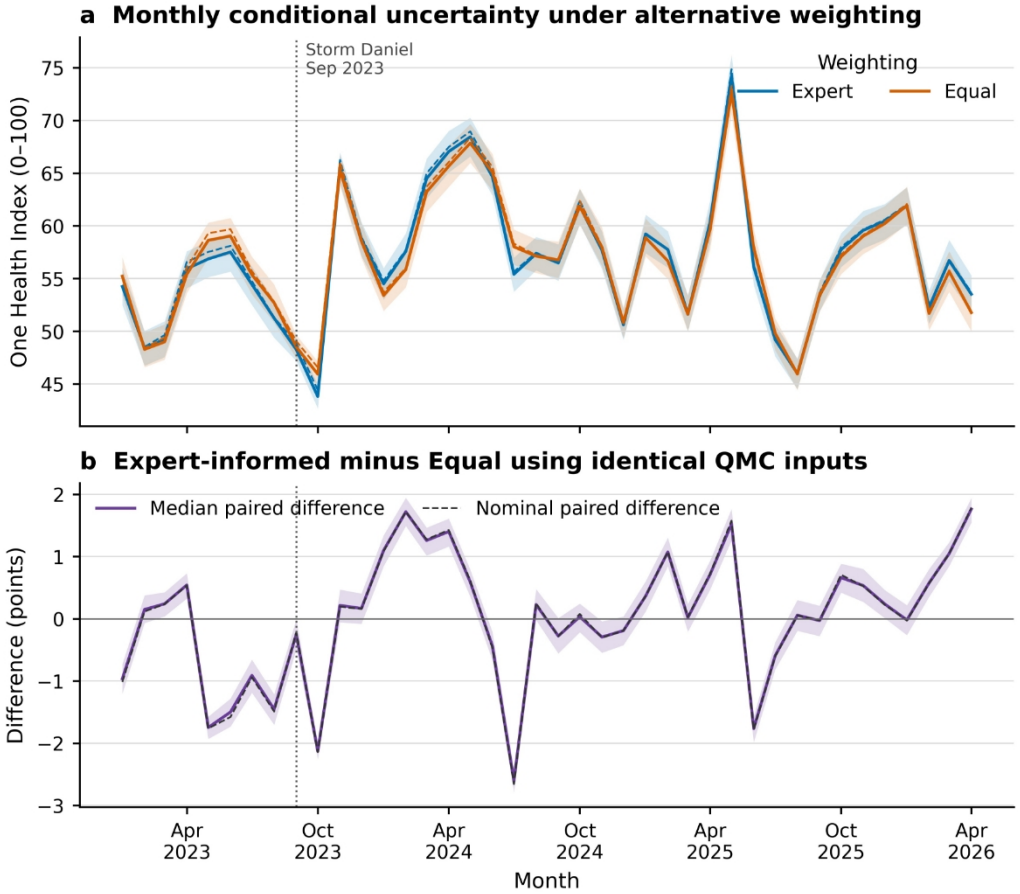


Figure 3. Monthly conditional uncertainty of OHI from January 2023 to April 2026. Solid lines show medians across 1,000 matched Sobol-sequence runs, shaded bands show 2.5th–97.5th percentile simulation intervals and dashed lines show nominal runs. Panel b reports matched Expert-minus-Equal differences; the horizontal line denotes no weighting difference. The September 2023 marker provides temporal context for Storm Daniel and is not an attribution estimate. In panel a, the vertical axis is restricted to the displayed range rather than the full 0–100 index scale.

3.2 April 2026 robustness and weighting effect

In April 2026, nominal OHI was 53.69 under expert-informed weighting and 51.91 under equal weighting (Table 1). Across 1,000 runs, the expert-informed OHI mean was 53.55, the median 53.52 and the conditional 95% simulation interval 51.74–55.29. The corresponding equal-weighted values were 51.80, 51.78 and 50.00–53.58. Coefficients of variation were 1.74% and 1.76%, respectively.

The matched April 2026 OHI difference averaged 1.76 points, with a median of 1.76 and a conditional 95% interval of 1.54–1.94; it was positive in every run (Table 2). This is 1.76% of the full 0–100 scale. Because no externally validated status classes or decision thresholds exist for this sample-relative index, the result establishes a systematic numerical shift under the specified test but not a management-relevant change of status. Expert-informed weighting lowered HHI by 0.82 points and WQI by 0.47 points on average, while increasing AAHI by 3.42 and EHI by 2.67. The distributions are shown in Fig. 4.

Table 1. April 2026 conditional uncertainty summary by weighting scenario. P2.5 and P97.5 are simulation-percentile bounds across 1,000 quasi-Monte Carlo runs, not confidence limits. AAHI is the operational Stella label and is interpreted here as an aquatic habitat-condition proxy; it maps only partially to the published AAHRI domain. WQI is the operational model label for a nested six-variable pressure sub-index whose sampling provenance is incompletely documented.

Scenario	Index	Nominal	Mean ± SD	Median	P2.5	P97.5
Expert	OHI	53.69	53.55 ± 0.93	53.52	51.74	55.29
Expert	HHI	57.12	56.94 ± 1.07	56.96	54.80	58.92
Expert	AAHI	47.83	47.67 ± 1.27	47.67	45.07	50.02
Expert	EHI	56.13	56.05 ± 0.93	56.01	54.27	57.95
Expert	WQI	49.20	49.20 ± 1.16	49.18	46.98	51.41
Equal	OHI	51.91	51.80 ± 0.91	51.78	50.00	53.58
Equal	HHI	57.92	57.76 ± 1.05	57.73	55.63	59.77
Equal	AAHI	44.37	44.25 ± 1.18	44.24	41.92	46.52
Equal	EHI	53.44	53.39 ± 0.87	53.35	51.66	55.19
Equal	WQI	49.68	49.68 ± 1.17	49.67	47.43	51.90

Table 2. Matched April 2026 differences between weighting scenarios. Differences are Expert-informed minus Equal; intervals are conditional simulation percentiles. Values were calculated from unrounded matched run-level outputs and may therefore differ by 0.01 from differences calculated using the rounded means in Table 1.

Index	Mean Δ	Median Δ	P2.5	P97.5	Expert > Equal
OHI	1.76	1.76	1.54	1.94	100.0%
HHI	-0.82	-0.81	-1.40	-0.27	0.0%
AAHI	3.42	3.46	3.00	3.77	100.0%
EHI	2.67	2.68	2.33	2.99	100.0%
WQI	-0.47	-0.47	-0.80	-0.16	0.0%

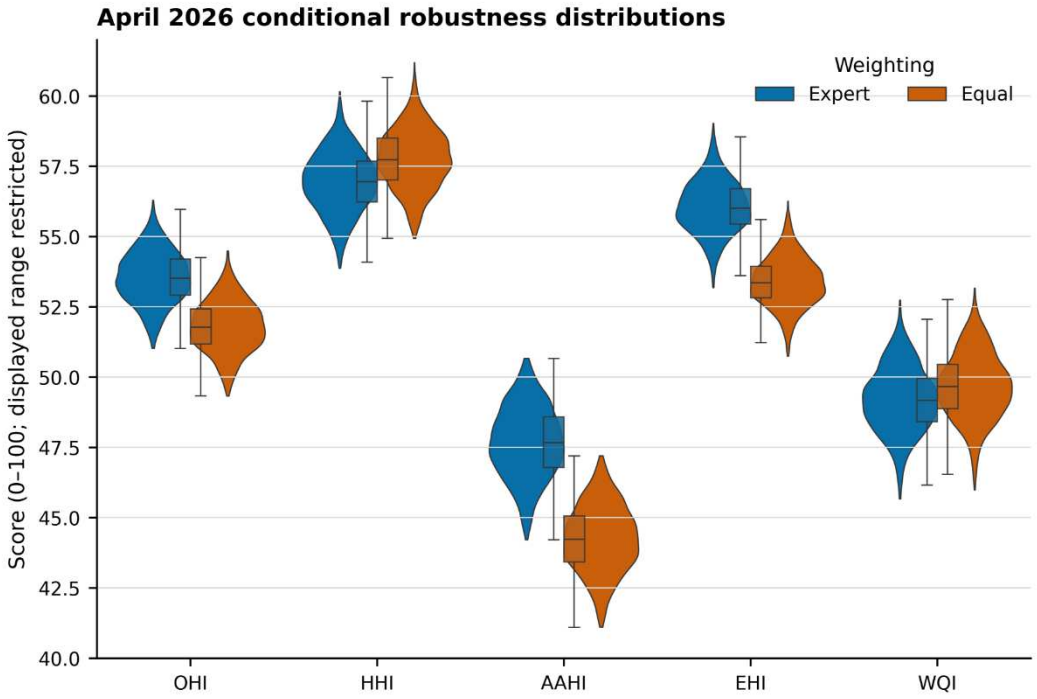


Figure 4. April 2026 conditional robustness distributions of the composite and pillar/sub-index outputs. Violin widths represent empirical density across 1,000 matched runs and internal boxplots denote the median and interquartile range. The vertical axis is restricted to the observed range (approximately 40–62), rather than the full 0–100 index scale, to show distributional detail.

3.3 Conditional contribution sensitivity and convergence

Within the ±10% score-contribution experiment, the April 2026 OHI response was nearly linear: SRC metamodel R^2 was 0.9801 under expert-informed weighting and 0.9847 under equal weighting. DO, chlorophyll-a and pH had the largest standardised responses in both scenarios (Fig. 5): 0.540, 0.515 and 0.455 under expert-informed weighting and 0.489, 0.553 and 0.487 under equal weighting. Their normalised squared-SRC shares totalled 76.3% and 77.7%. These rankings describe perturbations of the harmonised contribution scale and partly reflect structural reuse and effective weight; they do not mean that increasing a raw pressure improves health, nor do they identify causal environmental drivers.

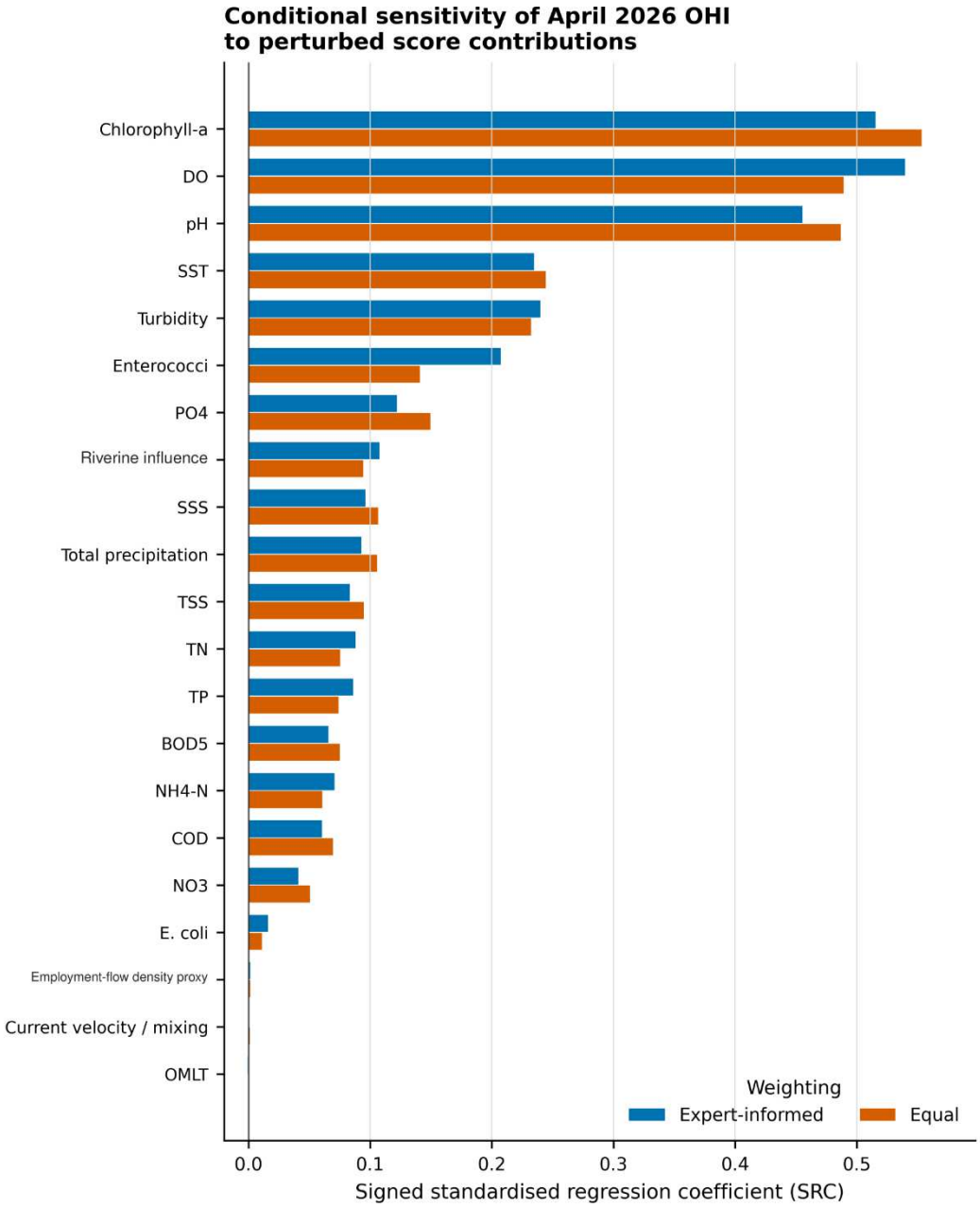


Figure 5. Conditional contribution sensitivity of April 2026 OHI. Bars are signed SRCs from regressions of OHI on the 21 Sobol-design multiplier dimensions applied to already-normalised score contributions. They are not raw-variable sensitivities, causal effects, monitoring-priority scores or Sobol variance-decomposition indices. SSS, sea-surface salinity; SST, sea-surface temperature; OMLT, ocean mixed-layer thickness; RIV, Riverine influence.

The ordering was numerically stable across nested prefixes. At n=128, Spearman correlation between the absolute-SRC ordering and the 1,000-point ordering was 0.983 for expert-informed weighting and 0.982 for equal weighting; the five leading contributions were identical. The n=128 mean April 2026 OHI differed from the full-sample mean by less than 0.004 points. Supplementary Fig. S1 presents selected mean and rank-correlation diagnostics; the complete numerical diagnostics, cross-output SRC matrix and exact coefficients are provided in Supplementary Data 1, with the SRC matrix visualised in Supplementary Fig. S2.

4. Discussion

4.1 Conditional robustness and weighting

The paired design supports two limited conclusions. First, OHI varied within narrow intervals when all 21 already-normalised contributions were multiplied within ±10%. This demonstrates numerical stability only for the specified bounded experiment; averaging in an additive hierarchy and the common narrow multiplier range make low dispersion plausible by construction. Second, the central 95% of matched April

2026 Expert-minus-Equal differences ranged from 1.54 to 1.94 points, and all 1,000 differences were positive. The shift is systematic within the experiment but small relative to the full scale, and its practical importance cannot be judged without validated decision bands or outcome-based calibration.

Pillar-level results reveal the mechanism obscured by the aggregate: expert-informed weights raised AAHI and EHI while lowering HHI and WQI. Thus, a higher OHI does not indicate uniform improvement. The effect also depends on the observed state, because the monthly Expert-minus-Equal sign changed over the series. Reporting the pillars and contributions alongside OHI is necessary to expose additive compensation [8,9].

4.2 Construct validity and interpretation of SRCs

The leading SRCs should not be translated directly into operational monitoring priorities. The multiplier dimensions targeted independent marginals and the realised Sobol design was effectively orthogonal, but the low-discrepancy points were not independent random draws. The perturbations were applied after normalisation. In a nearly linear weighted sum, a coefficient is governed mainly by the April 2026 score, the variable's effective weight, reuse across branches and clipping. A contribution at zero cannot respond to positive multiplicative perturbation, regardless of the raw variable's measurement uncertainty or ecological importance. Cost, observability, predictive value and empirically grounded uncertainty would be required for a defensible monitoring-priority analysis.

Construct validity remains unresolved and requires an explicit distinction between the published framework and the operational evidence. Ioannou et al. [11] define HHOI, AAHRI and EEQI as conceptual outcome-, risk- and ecosystem-quality domains. The present Stella implementation uses HHI, AAHI and EHI as shorter operational labels for data-constrained proxy branches; they are mappings rather than terminological equivalents. Five environmental variables—DO, turbidity, pH, SSS and chlorophyll-a—are reused in all three branches and carry about 51% of total effective leaf weight. HHI therefore represents exposure-related evidence rather than measured human health. AAHI is retained as the operational Aquatic Animal Health Index label, but its seven inputs—DO, turbidity, pH, SSS, chlorophyll-a, current velocity and OMLT—are environmental habitat variables, five of which are also used in EHI. It contains no observations of aquatic-animal morbidity, mortality, disease, pathology, biomarkers or population status and should be interpreted as an aquatic habitat-condition proxy, not a direct or statistically independent measure of animal health. No epidemiological, toxicological or veterinary endpoint was available for external validation.

More broadly, this operational implementation responds to recent calls for representative and harmonised indicators capable of quantifying regional One Health interdependencies and supporting place-based, cross-sectoral water governance [22].

4.3 Limitations and next steps

The scale is relative to the same 40-month series being evaluated. With only 40 monthly values, the type-7 P05 anchor lies between the second and third ordered observations and P95 between the 38th and 39th; both may therefore be sensitive to one or two atypical months. P05, P95 and the empirical median can also change when the observation window changes, and median-centred rules do not represent ecological optima or season-specific acceptable ranges. The index should consequently not be compared across periods or coastal systems without recalibration. External regulatory thresholds, historical reference conditions or seasonal climatologies should replace sample-relative anchors where defensible, and future applications should examine the stability of conclusions under alternative symmetric anchors such as P10–P90.

The missingness burden is substantial for microbial and several water-quality variables, deterministic completion narrows apparent variability, and TN lacks an independent imputation audit. The same ±10% perturbation envelope was intentionally applied to every normalised contribution to provide a common numerical stress test; it was not scaled by missingness because missingness proportion is not an empirical estimate of imputation error. Consequently, identical perturbation ranges do not imply equal evidential confidence across variables. In particular, the heavily completed microbial series remain more weakly supported than fully observed series even though their April 2026 SRCs are low. The experiment also omits uncertainty in imputation, empirical anchors, weights and structural choices, as well as dependence among

the underlying environmental variables. Future analyses should test variable-exclusion and multiple-imputation scenarios, propagate product- and assay-specific uncertainty and dependence from the raw scale, vary normalisation functions and bounds, and sample weight uncertainty.

Finally, the evidence base combines satellite ocean-colour observations, blended observational data, numerical marine-model products and local records at markedly different spatial resolutions. Gulf-wide monthly means may obscure short-lived or nearshore hotspots. Exact SST provenance, the NO3/PO4 vertical and temporal selection, file-level versions, retrieval timestamps and valid-pixel counts were not preserved. For the DEYAMB-linked records, the available files do not retain sufficient metadata to establish sampling matrix, methods or units independently. For RIV, the shared DEYAMB source family was identifiable, but complete derivation and independently verified unit metadata were not preserved. These gaps limit upstream reconstruction and interpretation, although they do not alter calculations on the supplied matrix. The representation of DEYAMB-linked information at both parameter and pathway levels creates a documented relationship between HHI and EHI. Agreement between these branches is therefore interpreted as internal coherence across related screening perspectives rather than as independent corroboration. Prospective validation should test whether habitat-based AAHI scores predict co-timed aquatic-animal outcomes, while HHI and OHI should be evaluated against appropriate exposure and population-health indicators. Until then, the indicator is a transparent screening synthesis for integrated surveillance and targeted follow-up, not an early-warning, regulatory or health-status instrument.

5. Conclusions

This study developed a hierarchical composite coastal One Health Indicator for the Pagasitikos Gulf by integrating Copernicus observation and marine-model products with local monitoring and administrative records. The operational branches comprise a human-exposure proxy, an Aquatic Animal Health Index interpreted as an aquatic habitat-condition proxy, an Environmental Health Index and a nested Water Quality Index. Equal and expert-informed intensity weighting were compared using matched quasi-Monte Carlo inputs. For April 2026, the mean paired Expert-minus-Equal OHI difference was 1.76 points and was positive in all 1,000 matched runs, while both conditional distributions remained narrow under simultaneous ±10% perturbation of normalised score contributions. DO, chlorophyll-a and pH showed the largest SRCs, but these coefficients reflect the specified additive score-space experiment, effective weights and cross-branch reuse rather than causal environmental influence or monitoring priority. The contribution is methodological: a baseline whose reported numerical summaries can be independently checked, challenged under alternative assumptions and progressively linked to direct epidemiological, toxicological and aquatic-animal outcomes. External validation, stable reference anchors, complete provenance and raw-scale uncertainty propagation are required before health-status, management or early-warning use.

Supplementary information

The Supplementary Information file contains detailed methods, Supplementary Table S1 and Supplementary Figs. S1–S2. Supplementary Data 1 is a curated analysis workbook containing the exact realised multiplier vectors, run-level final outputs, temporal and paired summaries, sensitivity coefficients, convergence diagnostics and parameter quality-assurance tables. Supplementary Data 2 contains the full numerical Stella Architect export for the Expert-informed and Equal weighting scenarios. No separate software package or native Stella model files accompany the submission.

Author contributions

Conceptualization, A.I., E.B., N.K., C.B. and C.L.; Methodology, A.I., E.B. and N.K.; Visualization, A.I., E.B. and N.K.; Model Implementation, A.I.; Writing—original draft preparation, A.I., E.B. and N.K.; Writing—review and editing, C.B. and C.L.; Supervision, C.B. and C.L.; Project administration, C.L.; Funding acquisition, C.L. All authors have read and approved the submitted version of the manuscript.

Funding

This work received funding from the European Union Space Programme under Grant Agreement No. 101180146, managed by the European Union Agency for the Space Programme (EUSPA).

Data availability

The processed data supporting the reported analyses are provided in Supplementary Data 1–2. Supplementary Data 1 contains the 40 × 21 normalised score matrix, the intended exact weights, the audited archived implementation coefficients, the realised 1,000 × 21 Sobol multiplier matrix, run-level outputs, temporal and paired summaries, sensitivity coefficients, convergence diagnostics and quality-assurance tables. Supplementary Data 2 contains the full numerical Stella Architect export for the expert-informed and equal-weight scenarios. Product identifiers, public source references, data-processing rules and known provenance limitations are reported in the Methods, Supplementary Information and the Data_Provenance sheet of Supplementary Data 1.

Code availability

Analysis scripts and the native Stella model files are available from the corresponding author upon reasonable request for peer-review and reproducibility purposes, subject to any applicable software-licence restrictions.

Competing interests

The authors declare no competing interests. The funders had no role in study design; data collection, analysis or interpretation; manuscript preparation; or the decision to submit the work for publication.

Disclaimer

Funded by the European Union. Views and opinions expressed are, however, those of the authors only and do not necessarily reflect those of the European Union or EUSPA. Neither the European Union nor EUSPA can be held responsible for them.

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