

RESEARCH ARTICLE

Integrated Coastal Engineering Analysis and Adaptive AHP Weighting for Objective Selection of Coastal Protection Structures at Bahoi Beach, North Minahasa

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ABSTRACT

Selecting a coastal protection structure is usually a sequence of disconnected steps: hydro-oceanographic analyses are run with separate tools, coastal damage assessment stops at a handling priority, and multi-criteria weights are elicited from expert questionnaires that are subjective and hard to replicate. This paper presents an integrated, computer-executed method—registered as an Indonesian simple-patent application—that chains four analyses into one decision. Coastal damage is assessed with Circular Letter SE 08/SE/M/2010, waves are hindcast with the Sverdrup–Munk–Bretschneider method and Gumbel extremes, tides are resolved by the Admiralty and least-squares methods, and sediment transport is computed with the CERC formula and the Dean number. Their outputs form a linking-variable vector from which the scores of twelve candidate structures on six criteria are calculated directly, while the Analytic Hierarchy Process (AHP) weights are generated automatically by scaling the effectiveness–cost and stability–cost comparisons with the regulatory area-importance coefficient. A two-level sensitivity analysis tests robustness. Applied to Bahoi Beach, North Minahasa, with 11 years of MERRA-2 wind (4,018 records), a 15-day tidal record and site sediment data, the method gives handling priority C (final weight 225.0), a 25-year design wave of 0.565 m, a mixed, mainly semidiurnal tide ($F = 0.534\text{--}0.582$), potential longshore transport of 474,010 m³/year and a transitional cross-shore state ($Nd = 4.404$). With $K = 1.50$ the weights are consistent ($CR = 0.033$) and beach vegetation rehabilitation ranks first (0.150), ahead of beach nourishment and revetment. The ranking is unchanged under $\pm 20\%$ field-data and $\pm 10\%$ weight perturbations and switches to revetment only if the verified design wave exceeds 2.5 m or erosion becomes the critical damage category. The method yields traceable, reproducible recommendations without expert panels or commercial software.

Keywords: coastal protection; analytic hierarchy process; adaptive criterion weighting; coastal damage assessment; wave hindcasting; sediment transport; Bahoi Beach

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1. Introduction

Coastal settlements in Indonesia are increasingly exposed to abrasion, wave overtopping and tidal inundation. Bahoï Beach, in West Likupang District, North Minahasa Regency, North Sulawesi, is a representative case: permanent houses and the mooring area of the fishing fleet stand directly on the beach, the shoreline has retreated year after year, and part of the settlement floods during high tides and storms [18], [7]. The village is at the same time a tourism village and a community-based Marine Protected Area, so any protection measure has to balance engineering performance, environmental value and social acceptance.

The range of available measures is wide—shore-parallel works (seawalls, revetments, bulkheads and sea dikes), shore-normal works (groynes and jetties), offshore works (detached and submerged breakwaters and artificial headlands) and soft measures (beach nourishment, sand bypassing and vegetation rehabilitation) [14], [20]. In practice, however, the choice among them is made with empirical relations applied in isolation—the Sverdrup–Munk–Bretschneider (SMB) method for waves, the Hudson formula for armour weight and the CERC formula for sediment transport [1], [9]—while environmental, social, cost and material aspects are judged qualitatively.

Previous work at Bahoï illustrates the resulting fragmentation. A concrete-block revetment was designed in 2024 and filed as simple patent application No. S00202412641, but the structure type was fixed in advance and never compared objectively with other options [7]. A 2025 study forecast 20-year shoreline change with the commercial CEDAS-NEMOS model and found a dynamic equilibrium [8]. A separate granted simple patent (No. IDS000009816) formalises coastal sediment-transport analysis, but its result is not linked to damage assessment, wave or tide analysis, nor used to select a structure [3]. Circular Letter SE 08/SE/M/2010 standardises the assessment of twelve damage parameters and introduces an area-importance coefficient, yet it ends at a handling priority [10].

Four limitations therefore persist: (i) damage assessment is not carried forward quantitatively into structure selection; (ii) multi-criteria weights—particularly in the Analytic Hierarchy Process (AHP)—are usually elicited from expert questionnaires, which are subjective, depend on stakeholder availability and are hard to replicate between sites [15], [4]; (iii) the scores of the alternatives are not derived from the hydro-oceanographic analysis of the site, so the decision cannot be traced back to data; and (iv) wave, tide and sediment analyses are performed piecemeal with different, partly commercial tools, reducing transparency.

This paper addresses these limitations with an integrated method that was developed under the Unsrat Superior Applied Research (RTUU) scheme and registered as a simple-patent application. Its contributions are threefold:

1. a single computational chain in which the outputs of damage assessment, wave hindcasting, tidal analysis and sediment transport are assembled into a linking-variable vector that directly determines the scores of every candidate structure;
2. an adaptive AHP weighting scheme in which the criterion weights are generated automatically from the regulatory area-importance coefficient, removing the need for expert questionnaires while preserving matrix consistency; and
3. a two-level sensitivity analysis that quantifies the robustness of the recommendation and the threshold conditions under which it changes, demonstrated on Bahoi Beach and compared with the existing revetment design.

2. Materials and Methods

2.1 Study Area and Data

Bahoi Village lies on the north coast of the Minahasa Peninsula facing the open Sulawesi Sea. It has been managed as a community-based Marine Protected Area since 2002 and is promoted as a tourism village. The eastern sector provides the dominant generation area, whereas the northern, south-western, western and north-western sectors are sheltered by the peninsula. The existing condition of the beach is shown in Figure 1, and the input data are summarised in Table 1.



Figure 1. Existing condition of Bahoi Beach, showing the settlement and stone wall directly behind the beach face and the fishing boats moored along the shore.

Table 1. Input data and sources for the Bahoi case study.

Input file	Source	Description
Site characteristics	Field survey; verified open sources	Protection objectives, beach type, land use, relative budget, local rock, coral reefs

Wind record	NASA POWER MERRA-2 [11]	Daily speed and direction, 2015–2025, 4, 018 records
Effective fetch	RTUU-K1 [7]	Eight sectors; dominant East, 98.124 km
Hourly water level	Tide gauge, Navy Main Base VIII Kairagi [7]	15 days (360 hourly readings)
Coastal damage	Field documentation, RTUU-K1 [7]	Levels of the 12 parameters of SE 08/SE/M/2010 [10]
Importance coefficient	SE 08/SE/M/2010 [10]	K = 1.50 (provincial tourism area and MPA)
Sediment parameters	RTUU-K1 [7]	$\rho_s = 2,650 \text{ kg/m}^3$; $\rho_w = 1,025 \text{ kg/m}^3$; porosity 0.4; D50; breaker angle 45°

2.2 Method Architecture

The method is executed by a computer processing unit and consists of nine units (Figure 2). The data input unit (10) reads seven structured files. Modules 1–4 (20–50) run the damage, wave, tide and sediment analyses; unit (60) assembles their outputs into the linking-variable vector; Module 5 (70) performs the AHP selection through adaptive weighting (71), catalogue screening (72), scoring (73) and consistency testing and ranking (74); the sensitivity module (80) tests robustness; and the output unit (90) reports the result. All steps are implemented in a single open Python program (numpy), run with one command on the input folder without manual adjustment.

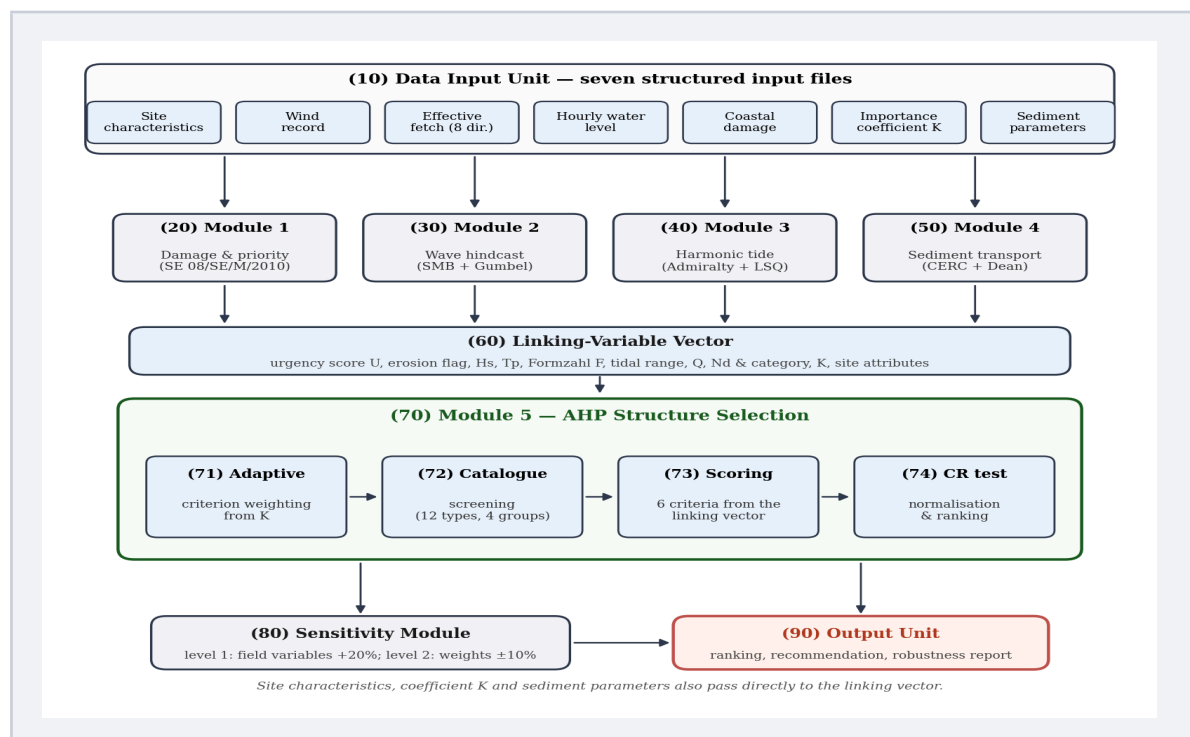


Figure 2. Architecture of the integrated method; numbers in parentheses denote the functional units.

2.3 Module 1: Coastal Damage Assessment and Urgency Score

Twelve parameters are assessed—environmental damage (L1–L8), erosion/abrasion and structural damage (EA1–EA2) and sedimentation (SP1–SP2)—each at five levels (light 50, moderate 100, severe 150, very severe 200 and extremely severe 250) [10]. The highest level weight W_i in each category is multiplied by the area-importance coefficient K , which ranges from 0.5 (unused land) to 2.0 (world-heritage conservation area):

$$W_f = W_i \times K \quad (1)$$

A final weight W_f above 300 gives priority A, 226–300 B, 151–225 C, 76–150 D and below 76 E. The category with the largest W_f is taken as the critical category, and its class is converted into an urgency score $U = 3.0, 2.25, 1.5, 0.75$ or 0.25 for classes A–E. This urgency score is the first link between damage assessment and structure selection.

2.4 Module 2: Wave Hindcasting and Design Wave

Each wind event is assigned to one of eight sectors, and only sectors with non-zero fetch are processed. The wind speed U measured at elevation z is corrected to 10 m, converted to the wind-stress factor U_A , and the effective fetch is limited by the duration-limited fetch F_d for a wind duration t [1]:

$$U_{10} = U (10/z)^{1/7}, \quad U_A = 0.71 U_{10}^{1.23} \quad (2)$$

$$F_d = (g t / 68.8 U_A)^{1.5} U_A^2 / g, \quad F = \min(F_{eff}, F_d) \quad (3)$$

$$H_s = 0.283 (U_A^2 / g) \tanh[0.0125 (gF / U_A^2)^{0.42}] \quad (4)$$

$$T_p = 7.54 (U_A / g) \tanh[0.077 (gF / U_A^2)^{0.25}] \quad (5)$$

Annual maxima of H_s are fitted with the Gumbel distribution using the reduced mean Y_n and reduced standard deviation S_n for the sample size [5], [19]:

$$H_T = \bar{H} + (\sigma_H / S_n) \cdot [-\ln(-\ln(1 - 1/T)) - Y_n] \quad (6)$$

The 25-year value is adopted as the design wave, and the storm wave period is taken as the mean T_p of events with H_s at or above the 95th percentile.

2.5 Module 3: Harmonic Tidal Analysis

The constituents M_2 , S_2 , N_2 , K_2 , K_1 , O_1 , P_1 , M_4 and MS_4 are resolved simultaneously by two methods—the Admiralty method, which projects each constituent separately, and least squares, which solves all constituents at once [13], [12]. When the record is shorter than the Rayleigh period $360/|\Delta\omega|$ hours of a constituent pair, K_2 , P_1 and N_2 are inferred from S_2 , K_1 and M_2 with ratios of 0.27, 0.33 and 0.19. The agreement of the two methods serves as an internal verification. The tidal type follows from the Formzahl number, and the tidal range is taken as HHWL – LLWL:

$$F = (A_{K1} + A_{O1}) / (A_{M2} + A_{S2}) \quad (7)$$

2.6 Module 4: Sediment Transport

The breaking-wave height, potential longshore transport (CERC) and dimensionless fall velocity (Dean number) are computed as [1], [2], [6]:

$$H_b = 0.39 g^{0.2} (T_p H_s^2)^{0.4} \quad (8)$$

$$Q = K_O \rho_w g^{1/2} H_b^{2.5} \sin 2\alpha_b / [16 (\rho_s - \rho_w)(1 - n)] \quad (9)$$

$$N_d = H_b / (w_s T_p) \quad (10)$$

where $K_Q = 0.39$, α_b is the breaker angle, n the porosity and w_s the fall velocity obtained from the Soulsby formula for the dimensionless grain size [17]. $N_d < 1$ is classed as accretion, 1–6 as transitional (dynamic equilibrium) and > 6 as erosion.

2.7 Linking-Variable Vector

Unit (60) assembles the outputs of Modules 1–4 and the site characteristics into a single vector: protection objectives, beach type, land use, relative budget, local rock availability, presence of coral reefs, coefficient K , urgency score U , an erosion flag (whether the critical category is erosion/abrasion), design H_s , T_p , Formzahl F , tidal range, longshore transport Q , Dean number N_d and its category. Every alternative score in Module 5 is computed from this vector, which makes each recommendation traceable to the underlying data.

2.8 Module 5: Adaptive AHP Structure Selection

Six criteria are used: technical effectiveness, structural stability, environmental impact, social acceptance, construction and maintenance cost, and local material availability. The procedure is shown in Figure 3(a). A base 6×6 pairwise comparison matrix is defined (Table 2). Instead of eliciting it from experts, the effectiveness–cost and stability–cost elements are scaled by the area-importance coefficient, clipped to the regulatory range, and the reciprocal elements are updated:

Table 2. Base pairwise comparison matrix of the six criteria (row versus column).

	Eff.	Stab.	Env.	Soc.	Cost	Mat.
Technical effectiveness	1	1	3	3	$2 \times K$	4
Structural stability	1	1	3	3	$2 \times K$	3
Environmental impact	1/3	1/3	1	2	1/2	2
Social acceptance	1/3	1/3	1/2	1	1/2	2

Construction & maintenance cost	1/(2K)	1/(2K)	2	2	1	3
Local material availability	1/4	1/3	1/2	1/2	1/3	1

Note: K = area-importance coefficient, clipped to $0.5 \leq K \leq 2.0$. With $K = 1$ the matrix reduces to the neutral base matrix.

$$a'_{12} = a_{12} \cdot K, \quad a'_{21} = 1 / a'_{12}, \quad 0.5 \leq K \leq 2.0 \quad (11)$$

where subscripts 1 and 2 denote a technical criterion (effectiveness or stability) and cost, respectively. The more important the area, the larger the weight of the technical criteria relative to cost. The weights w are the normalised principal eigenvector of the matrix, and consistency is checked with the random index $RI = 1.24$ for $n = 6$; the process stops if $CR > 0.10$ [16]:

$$A w = \lambda_{\max} w, \quad CR = (\lambda_{\max} - 6) / (5 \times 1.24) \quad (12)$$

The candidate set is then screened from a catalogue of twelve structure types in four groups (Table 3): only types that serve at least one protection objective of the site—T1 erosion, T2 overtopping, T3 beach width, T4 longshore transport, T5 river-mouth shoaling and T6 wave energy—and that suit the beach type are retained.

Table 3. Catalogue of coastal protection structures grouped by position.

Group	Position	Structure types
A	Shore-parallel, landward	Seawall, revetment, bulkhead, sea dike
B	Shore-normal	Groyne, jetty
C	Offshore	Detached breakwater, submerged breakwater, artificial headland
D	Soft protection	Beach nourishment, sand bypassing, beach vegetation rehabilitation

Each candidate is scored on the six criteria from the linking-variable vector according to the rules in Table 4. The scores s_{ij} are normalised per criterion and combined with the weights to give the total score S_i ; the candidate with the highest S_i is recommended:

$$\tilde{s}_{ij} = s_{ij} / \sum_i s_{ij}, \quad S_i = \sum_j w_j \tilde{s}_{ij} \quad (13)$$

Table 4. Scoring rules linking the site variables to the criterion scores.

Criterion	Scoring rule

Technical effectiveness	$0.4 + 0.25$ per objective served (max. 1.0); + $0.15 \cdot U/3$ for seawall and revetment if the critical category is erosion; + $0.20 \cdot \min(1, Q /200,000)$ for groyne, jetty and sand bypassing; + 0.15 if the Dean category is erosion and the type serves T1
Structural stability	By group and design Hs: > 2.5 m A 0.85, B 0.75, C 0.65, D 0.40; 1.0–2.5 m A 0.80, B 0.75, C 0.75, D 0.55; ≤ 1.0 m A 0.70, B 0.70, C 0.75, D 0.80; + 0.10 for seawall and sea dike if the tidal range exceeds 2.0 m
Environmental impact	A 0.40, B 0.55, C 0.65, D 0.90; × 0.7 for offshore types where coral reefs are present
Social acceptance	0.90 for nourishment and vegetation; 0.80 for group A in settlement, fishing or vital-infrastructure areas; 0.85 for groups C and D in tourism areas; 0.60 otherwise
Construction and maintenance cost	Relative cost of each type, × 1.2 for a low budget or × 0.85 for a high budget; + 0.05 for revetment, nourishment and vegetation if $U \geq 2.0$
Local material availability	Depends on local rock availability for rock-based types; 0.75 for group D

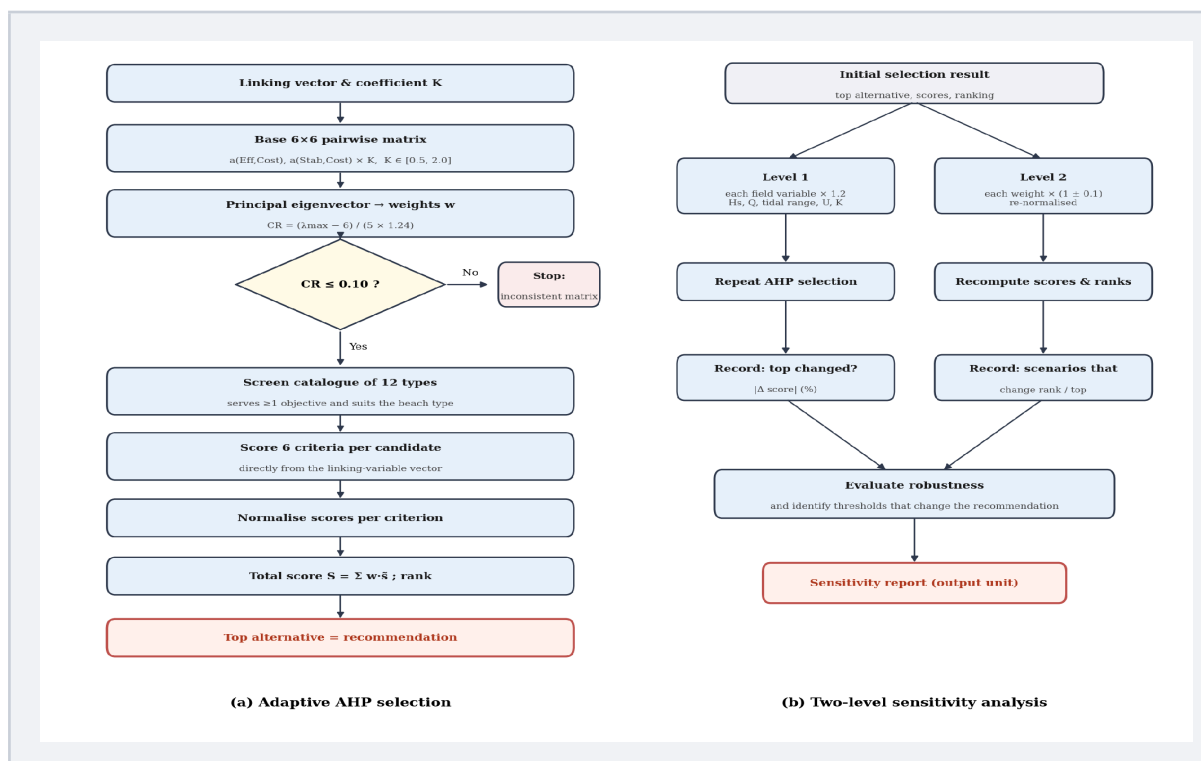


Figure 3. (a) Adaptive AHP selection procedure; (b) two-level sensitivity analysis.

2.9 Sensitivity Analysis and Validation

Robustness is examined on two levels (Figure 3(b)). At the first level, each field variable in the linking vector—design H_s , Q , tidal range, U and K —is increased by 20% and the selection is repeated, recording whether the top alternative changes and the percentage change in its score. At the second level, each criterion weight is multiplied by $(1 - 0.1)$ and $(1 + 0.1)$ and re-normalised, and the number of scenarios that change the ranking or the top alternative is recorded. The results are evaluated to state the robustness of the recommendation and the thresholds that would change it. The recommendation is further validated against the existing RTUU-K1 revetment design [7].

3. Results and Discussion

All modules were executed end-to-end on the Bahoi data without computational failure, corresponding to Technology Readiness Level (TRL) 4—validation with secondary and independent real data in a controlled simulation environment.

3.1 Coastal Damage and Handling Priority

Because Bahoi Beach is both a fishing settlement (local importance, $K = 1.00$) and a provincial-level tourism village and Marine Protected Area ($K = 1.50$), a coefficient of 1.50 was adopted. Two parameters were relevant to the documented conditions (Table 5). The critical category is environmental damage (L1, houses inundated during high tides), giving handling priority C with a final weight of 225.0 and an urgency score $U = 1.5$. Because the critical category is L1 rather than EA1, the erosion flag in the linking vector is off.

Table 5. Coastal damage assessment (Form 2, SE 08/SE/M/2010).

Parameter	Level	Weight	Final weight	Priority
L1 – Coastal environmental damage	B (severe)	150	225.00	C – Prioritised
EA1 – Erosion/abrasion and structural damage	S (moderate)	100	150.00	D – Less prioritised

Note: $K = 1.50$. Damage levels are conservative estimates based on qualitative field documentation.

3.2 Wave Climate and Design Wave

The North, South-West, West and North-West sectors have no fetch. Of the remaining sectors (Table 6) the South produces the most events, but the East, with the longest fetch, generates the largest waves (H_s max = 0.468 m). The Gumbel design waves are given in Table 7 and Figure 4.

Table 6. SMB hindcast wave statistics by sector (2015–2025).

Sector	Events	H_s max (m)	H_s mean (m)	T_p mean (s)
North-East	519	0.099	0.034	0.662

East	250	0.468	0.138	1.474
South-East	373	0.236	0.073	1.027
South	1, 064	0.246	0.078	1.040

Table 7. Design significant wave height by return period (Gumbel).

Return period (years)	2	5	10	25	50	100
Hs (m)	0.350	0.436	0.493	0.565	0.618	0.672

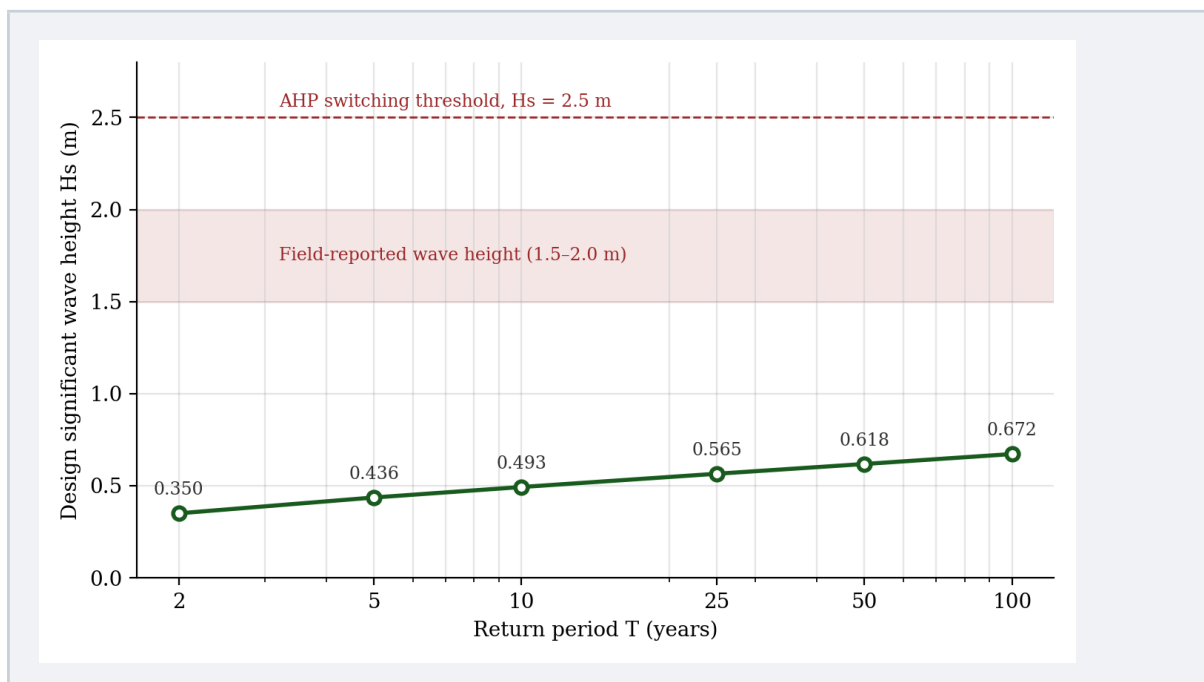


Figure 4. Design wave height versus return period compared with the field-reported wave range and the switching threshold of the structural-stability score.

The 25-year design wave (0.565 m) is far below the 1.5–2.0 m waves reported in the field; RTUU-K1 had noted a similar gap between its hindcast (0.683 m) and observations [7]. The fetch-limited SMB method represents only locally generated wind sea and does not capture swell arriving from the open Sulawesi Sea and Pacific Ocean. This is the most influential uncertainty in the results and is discussed further in Section 3.8.

3.3 Tidal Characteristics

The Admiralty and least-squares analyses gave Formzahl numbers of 0.5820 and 0.5336; both classify the tide as mixed, mainly semidiurnal. The two methods agree closely, with reconstruction errors of 0.063 m and 0.060 m and nearly identical datums (Table 8). The tidal range (HHWL – LLWL) is 1.65 m, below the 2.0 m threshold that would raise the stability score of seawalls and sea dikes.

Table 8. Reference water levels at Bahoi Beach.

Datum	Admiralty (m)	Least squares (m)
HHWL	2.0201	2.0338
MHWS	1.8181	1.8194
MSL	1.1975	1.1985
MLWS	0.5769	0.5777
LLWL	0.3749	0.3633

Note: HHWL = highest high water level; MHWS = mean high water springs; MSL = mean sea level; MLWS = mean low water springs; LLWL = lowest low water level.

3.4 Sediment Transport

The potential longshore transport is 474,010.4 m³/year in the positive direction (from the East). The Dean number of 4.404 places the cross-shore regime in the transitional class, indicating a dynamic balance between onshore and offshore transport. This agrees qualitatively with the CEDAS-NEMOS forecast, which reported an accretion–erosion difference below 0.35% [8], although the two results come from different approaches. The longshore value is a potential rate, since the CERC formula assumes an unlimited sediment supply.

3.5 Linking-Variable Vector for Bahoi Beach

The hydro-oceanographic outputs that enter the scoring are summarised in Table 9. Their combination explains the ranking obtained in Section 3.7: a low design wave, a moderate tidal range, a transitional Dean category and a non-erosion critical category.

Table 9. Hydro-oceanographic components of the linking-variable vector for Bahoi Beach.

Variable	Value	Source
Area-importance coefficient K	1.50	SE 08/SE/M/2010
Urgency score U (priority C)	1.5	Module 1
Critical category is erosion/abrasion	No (L1)	Module 1
Design wave H _s (T = 25 years)	0.565 m	Module 2
Formzahl F (Admiralty)	0.5820	Module 3
Tidal range (HHWL – LLWL)	1.65 m	Module 3
Longshore transport Q	474, 010.4 m ³ /year	Module 4
Dean number Nd (category)	4.404 (transitional)	Module 4

3.6 Adaptive Criterion Weights

Table 10 compares the weights obtained with the neutral coefficient (K = 1.00) and with the Bahoi coefficient (K = 1.50). Raising K shifts about 2.2 percentage points of weight from cost to technical effectiveness (0.288 → 0.302) and 1.5 points to structural stability (0.277 → 0.292), while the cost weight falls from 0.171 to 0.149; the other criteria change only marginally. Figure 5 extends the analysis over the full admissible range $0.5 \leq K \leq 2.0$: the weights vary smoothly and monotonically, and CR stays between 0.016 and 0.048, well within the 0.10 limit. The adaptive scheme therefore

encodes the policy intent of the regulation—more important areas warrant more technically robust protection—without degrading consistency or requiring an expert panel.

Table 10. AHP criterion weights for the neutral and the Bahoi importance coefficient.

Criterion	K = 1.00	K = 1.50 (Bahoi)
Technical effectiveness	0.2877	0.3020
Structural stability	0.2774	0.2921
Environmental impact	0.1126	0.1092
Social acceptance	0.0889	0.0865
Construction and maintenance cost	0.1706	0.1487
Local material availability	0.0628	0.0615
Consistency ratio CR	0.0202	0.0329

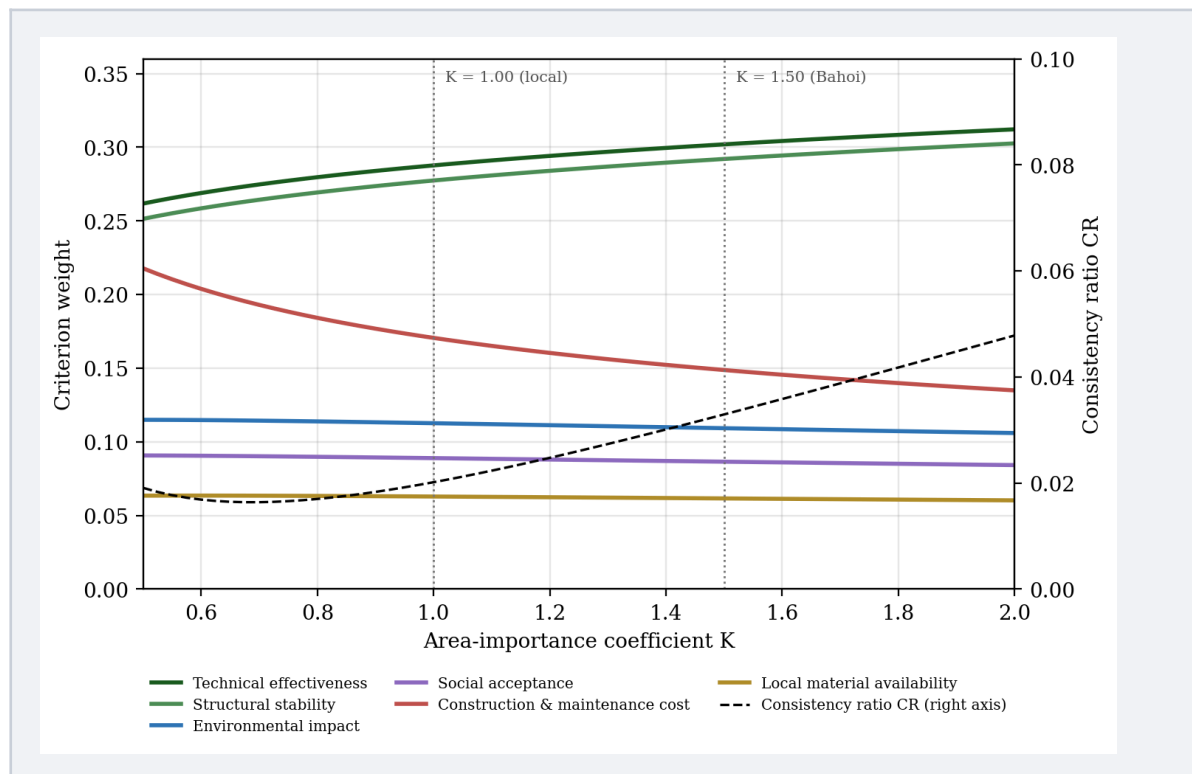


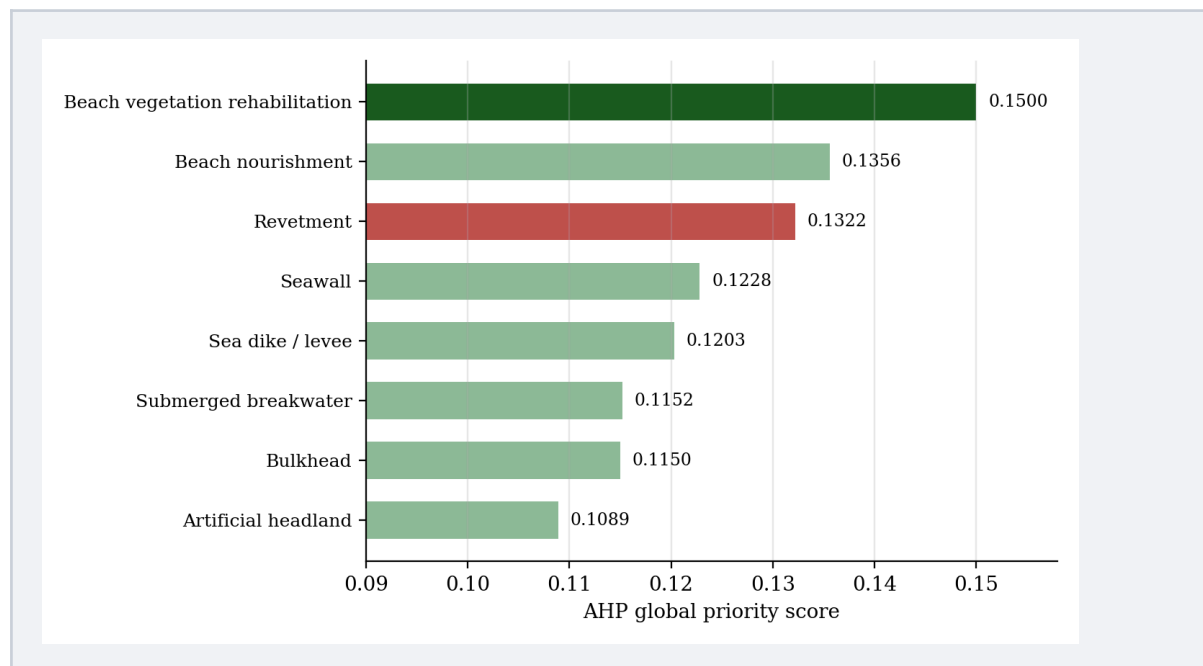
Figure 5. Response of the criterion weights and consistency ratio to the area-importance coefficient over its admissible range.

3.7 Structure Ranking

Eight of the twelve catalogue types passed the screening; groyne, jetty, detached breakwater and sand bypassing did not match the site objectives or beach type. The ranking of the remaining candidates is given in Table 11 and Figure 6.

Table 11. Ranking of coastal protection alternatives ($K = 1.50$).

Rank	Alternative	Group	AHP score
1	Beach vegetation rehabilitation (mangrove casuarina) /	D	0.1500
2	Beach nourishment	D	0.1356
3	Revetment	A	0.1322
4	Seawall	A	0.1228
5	Sea dike / levee	A	0.1203
6	Submerged breakwater	C	0.1152
7	Bulkhead	A	0.1150
8	Artificial headland	C	0.1089

**Figure 6.** AHP total scores of the eight screened alternatives; the patented RTUU-K1 revetment ranks third.

Beach vegetation rehabilitation ranks first, followed by beach nourishment and revetment. The scoring rules make the reason explicit. With a design wave below 1.0 m, soft protection (group D) receives the highest stability score (0.80 against 0.70 for group A), and it also scores highest on environmental impact (0.90) and social acceptance (0.90). Because the critical category is L1 rather than erosion, the revetment receives no urgency bonus on technical effectiveness. The result thus differs from the concrete-block revetment designed and patented in RTUU-K1 [7] for traceable reasons rather than by judgement.

3.8 Sensitivity and Switching Thresholds

Table 12. Level 1: sensitivity of the ranking to field variables (+20%).

Variable	Source	Top changed alternative	Δ score (%)
Tidal range	Module 3	No	0.87
Area-importance coefficient	SE 08/SE/M/2010	No	0.68
Design wave height (Hs)	Module 2	No	0.00
Longshore transport (Q)	Module 4	No	0.00
Urgency score (U)	Module 1	No	0.00

Table 13. Level 2: sensitivity of the ranking to criterion weights ($\pm 10\%$).

Criterion	Scenarios with a rank change	Top alternative changed
Technical effectiveness	0 / 2	No
Structural stability	0 / 2	No
Environmental impact	0 / 2	No
Social acceptance	1 / 2	No
Construction and maintenance cost	1 / 2	No
Local material availability	1 / 2	No

No field variable changes the top alternative within +20%; the tidal range is the most influential ($|\Delta \text{score}| = 0.87\%$). None of the 12 weight scenarios alters the top alternative, and the three rank changes observed are limited to swapping sixth and seventh places between the submerged breakwater and the bulkhead, whose scores are almost equal (0.1152 and 0.1150). The recommendation is therefore robust to the weights and to moderate data errors. The zero effect of H_s , however, arises because $0.565 \text{ m} \times 1.2$ remains in the $\leq 1.0 \text{ m}$ stability class. Direct tests on the model show that revetment becomes the top alternative when (a) the design wave exceeds 2.5 m, where group A scores 0.85 against 0.40 for group D, and/or (b) the critical category shifts to EA1 once an abrasion rate of at least 1 m/year is verified, activating the urgency bonus. Since the field-reported waves (1.5–2.0 m) approach this threshold, the divergence from the RTUU-K1 design most likely reflects the under-estimation of swell by fetch-limited hindcasting rather than an inadequacy of the revetment.

3.9 Implications, Novelty and Limitations

Compared with the prior approaches, the method (i) carries damage assessment forward quantitatively through the urgency score and erosion flag, (ii) replaces expert questionnaires with weights generated from a regulatory coefficient, (iii) derives every alternative score from the site data through explicit rules, and (iv) runs all analyses in one open program, independent of commercial licences. Its value lies as much in stating the conditions under which the recommendation would change as in the recommendation itself, which gives agencies a clear agenda for data collection before committing to a structure.

The results are nevertheless conditional on the inputs. The main limitations are the fetch-limited wave hindcast, the qualitative damage documentation (the number of affected houses and the exact abrasion rate are not yet available), the regional standard D_{50} used in place of sieve analysis, the 15-day tidal record and the fact that the scoring coefficients, although explicit, are engineering judgements fixed in the method. The next stage will verify the design wave by scheduled visual observation, satellite altimetry and/or a wave-rider buoy; quantify multi-year shoreline retreat from satellite imagery with DSAS; carry out a census of houses within storm-wave reach and sieve tests; implement and calibrate a one-line shoreline model against the CEDAS-NEMOS forecast [8]; and confirm the recommendation in expert-judgement sessions towards TRL 5.

4. Conclusion

An integrated, computer-executed method was developed for selecting coastal protection structures, in which the outputs of damage assessment, wave hindcasting, tidal analysis and sediment transport form a linking-variable vector that determines the scores of twelve candidate structures, while the AHP weights are generated automatically from the regulatory area-importance coefficient. Applied to Bahoi Beach, the method gives handling priority C (final weight 225.0), a 25-year design wave of 0.565 m, a mixed, mainly semidiurnal tide ($F = 0.534\text{--}0.582$), a potential longshore transport of 474,010 m^3/year and a transitional cross-shore state ($N_d = 4.404$). With $K = 1.50$ the weights shift towards technical criteria while remaining consistent ($CR = 0.033$), and beach vegetation rehabilitation ranks first, ahead of beach nourishment and revetment. The ranking is robust to $\pm 20\%$ field-data and $\pm 10\%$ weight perturbations and switches to revetment only if the verified design wave exceeds 2.5 m or erosion becomes the critical damage category. Field verification of the design wave is therefore the decisive next step before a final design is adopted. The method offers local agencies an objective, transparent and replicable procedure that does not depend on expert panels or commercial software.

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