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A MULTI-CRITERIA RISK ASSESSMENT FRAMEWORK FOR IDENTIFYING CRITICAL SYSTEMS, ENVIRONMENTAL VULNERABILITIES, AND INFRASTRUCTURE PRIORITIES

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ABSTRACT

Decisions about which infrastructure systems to protect, repair, or upgrade first are difficult in settings where data are incomplete and environmental pressures compete with service demands. This study proposes a transparent multi-criteria risk assessment framework that integrates three dimensions: system criticality, environmental vulnerability, and infrastructure condition deficit. The framework combines the Analytic Hierarchy Process (AHP) for criterion weighting, min-max normalisation of indicators, and weighted linear combination to produce a composite Infrastructure Priority Index (IPI) and four priority classes. Interdependency among systems is treated as an explicit criterion, and spatial indicators can be derived through GIS overlay. The framework is demonstrated on a synthetic dataset of six hypothetical assets (water, electricity, health, transport, telecommunications, and solid waste) to show how weights, consistency checks, rankings, and sensitivity analyses are computed. The data are illustrative and are not empirical observations. In the demonstration, all pairwise comparison matrices achieved consistency ratios below 0.10, the water treatment plant ranked first in all 10,000 Monte Carlo weight perturbations, and mid-ranked assets exchanged positions under weight uncertainty, showing where decision-makers should concentrate verification effort. The framework is modular, reproducible, and adaptable to local indicator sets, and it provides a basis for field application and expert-elicited weighting in data-limited regions.

Keywords: Multi-Criteria Decision Analysis; Analytic Hierarchy Process; Critical Infrastructure; Environmental Vulnerability; Risk Assessment; Infrastructure Prioritisation

1 INTRODUCTION

Decisions about where to build, protect, or upgrade infrastructure are rarely driven by a single factor. Multi-criteria evaluation and the analytic hierarchy process (AHP) have been used to select a final solid waste disposal site in the Bolgatanga municipality of Ghana [1], and environmental modelling has been used to characterise the soil water balance of an agricultural watershed served by an irrigation dam [2]. Related work has integrated soil, water, and plant processes to improve fertiliser and irrigation efficiency in smallholder farming systems [3], and robotic solutions have

been discussed for precision agriculture [4]. These studies show that environmental and engineered systems are routinely analysed together, yet each study typically addresses one asset type or one decision.

Spatial multi-criteria assessment has also been applied to the selection of a solid waste disposal site within the Wa Municipality [5]. Environmental chemistry research on cyanobacterial extracellular polysaccharides produced at high CO₂ reports enhanced sequestration of heavy metals into mineral precipitate [6], which illustrates how contaminant processes in the environment bear on the management of engineered systems. GIS and AHP have been combined to map artificial groundwater recharge zones in the White Volta Basin of Ghana [7], and multi-temporal imagery has been used to assess agro-ecological change following construction of the Tono Reservoir [8]. The latter example is a reminder that infrastructure is not only exposed to environmental hazards but also reshapes the environment around it.

A parallel literature examines infrastructure as a network. Work on critical transit infrastructure and urban air quality compares ridership and PM_{2.5} across cities and seasons [9]. Other studies model intra- and inter-dependencies between power and communication systems [10], maintain self-updating contingency lists for smart grids [11], and identify the K most vulnerable entities in a smart grid [12]. These contributions provide concepts, namely dependency, contingency, and ranking of vulnerable entities, that are directly relevant to deciding which systems are critical.

Despite this progress, the two strands remain largely separate. Multi-criteria and GIS-based approaches are usually applied to siting or suitability problems, whereas network vulnerability approaches are usually confined to a single sector and rarely include environmental exposure. Practitioners in data-limited regions therefore lack a compact, reproducible method that ranks existing assets by considering how critical they are, how exposed they are to environmental stressors, and how poor their present condition is. This study addresses that gap by building on AHP [13], GIS-based multicriteria decision analysis [14], and the analysis of infrastructure interdependencies [15]. The objectives are to (i) define a three-dimensional framework for criticality, environmental vulnerability, and condition deficit; (ii) specify a weighting, aggregation, and classification procedure with built-in consistency and sensitivity checks; and (iii) demonstrate the procedure on an illustrative dataset and discuss its limitations and routes to field application.

2 MATERIALS AND METHODS

2.1 Framework overview

The framework has five steps (Figure 1): (1) define the scope and inventory of assets; (2) select indicators and assemble data; (3) derive criterion weights with AHP and normalise indicators; (4) compute the three dimension indices and the composite Infrastructure Priority Index (IPI); and (5) assign priority classes and test sensitivity. The three dimensions are the Criticality Score Index (CSI), the Environmental Vulnerability Index (EVI), and the Infrastructure Condition Deficit (ICD).

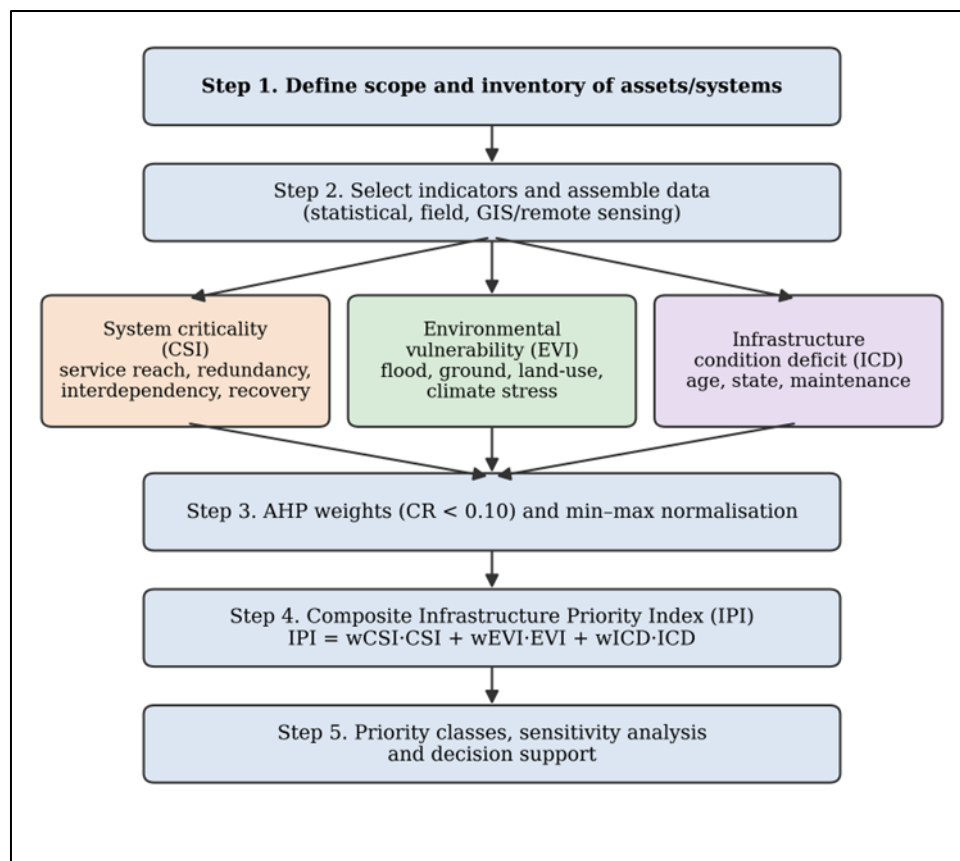


Figure 1: Workflow of the proposed multi-criteria risk assessment framework.

2.2 Scope, assets, and indicators

The analyst first defines the spatial and administrative boundary and lists the assets to be ranked (for example, treatment plants, substations, hospitals, transit hubs, telecommunications nodes, and waste facilities). Indicators are then chosen for each dimension. Table 1 gives the indicator set used in this paper. Indicators may be replaced to suit local data, provided each is assigned a direction (higher values increase risk or priority) and a measurable data source.

Table 1: Indicator set used to define the three dimensions.

Dimension	Indicator	Direction	Possible data source
CSI	C1 Population or services served	Benefit	Utility records, census, service-area GIS layers
CSI	C2 Redundancy deficit	Benefit	Network topology; presence of backup supply
CSI	C3 Interdependency	Benefit	Dependency matrix (Section 2.5)
CSI	C4 Recovery time	Benefit	Operator estimates; historical outage records
EVI	E1 Flood exposure	Benefit	Flood hazard maps; elevation and drainage layers
EVI	E2 Ground and erosion susceptibility	Benefit	Soil and slope layers
EVI	E3 Land-use pressure	Benefit	Land-cover maps; multi-temporal imagery
EVI	E4 Climate stress	Benefit	Rainfall intensity and temperature records
ICD	Condition deficit	Benefit	Age, inspection score, maintenance backlog

Direction 'Benefit' indicates that higher raw values increase the index; 'Cost' indicators would be inverted during normalisation.

2.3 AHP weighting and consistency

Criterion weights are derived with AHP [13]. For n criteria, experts compare each pair on the 1–9 Saaty scale, producing a reciprocal matrix

$$A = [a_{jk}], \quad a_{kj} = 1 / a_{jk}, \quad a_{jj} = 1 \quad (1)$$

The weight vector is the normalised principal eigenvector of A . Judgement consistency is checked with the consistency index (CI) and consistency ratio (CR):

$$CI = (\lambda_{\max} - n) / (n - 1), \quad CR = CI / RI \quad (2)$$

where $\lambda_{\max}$ is the principal eigenvalue and RI is the random index for matrices of order n . A matrix is accepted when $CR < 0.10$ [13]. Where several experts participate, individual matrices should be aggregated by the geometric mean before the eigenvector is computed. In this demonstration, a single set of judgements was specified by the authors for illustration.

2.4 Normalisation and index construction

Raw indicator values x_{ij} for asset i and indicator j are rescaled to $[0, 1]$ by min–max normalisation, using $(x_{ij} - \min x_j) / (\max x_j - \min x_j)$ for benefit indicators and the complement for cost indicators:

$$x'_{ij} = (x_{ij} - \min x_j) / (\max x_j - \min x_j) \quad (3)$$

Dimension indices are weighted linear combinations of the normalised indicators, and the composite index combines the three dimensions:

$$CSI_i = \sum_j w_j^C c_{ij}, \quad EVI_i = \sum_k w_k^E e_{ik} \quad (4)$$

$$IPI_i = w_1 CSI_i + w_2 EVI_i + w_3 ICD_i \quad (5)$$

Weights at each level sum to one. The IPI lies between 0 and 1. Weighted linear combination is compensatory, so a low value on one dimension can be offset by high values on others. This property is discussed in Section 3.4. Spatial indicators (for example E1–E3) may be computed by GIS overlay of hazard and land-cover layers and sampled at asset locations [14].

2.5 Treatment of interdependency

Interdependency (C3) is derived from a dependency matrix S in which $s_{mi} \in [0, 1]$ is the degree to which system m depends on asset i for its operation. The interdependency score of asset i is the column sum $d_i = \sum_{m \neq i} s_{mi}$, which is then normalised using Equation 3. This follows the idea, common in the interdependency literature [10,15], that the importance of an asset depends on what else fails when it fails. Contingency-based ranking of vulnerable entities [11,12] could replace this simple count in applications where network data are available. The demonstration does not simulate cascading failures.

2.6 Priority classes and sensitivity analysis

Assets are ranked by IPI and assigned to four classes using user-defined thresholds: Priority 1 ($IPI \geq 0.70$), Priority 2 ($0.60-0.699$), Priority 3 ($0.55-0.599$), and Priority 4 (< 0.55). The thresholds are illustrative and should be calibrated to the local decision context. Sensitivity was examined in two ways. First, each top-level weight was changed by $\pm 20\%$ in turn, with the others rescaled to sum to one. Second, a Monte Carlo experiment drew 10,000 weight vectors from a Dirichlet distribution centred on the base weights,

$$w \sim \text{Dirichlet}(\kappa \bar{w}), \quad \kappa = 30 \quad (6)$$

and recorded the rank of each asset in each draw. The concentration $\kappa = 30$ produces moderate perturbation around the base weights.

2.7 Illustrative dataset, software, and ethics

Six hypothetical assets were created to demonstrate computation: a water treatment plant, a primary substation, a regional hospital, a transit hub, a telecommunications switching centre, and a solid waste disposal site. Their normalised indicator values were assigned by the authors and do not describe real facilities, so none of the results should be read as findings about any real location. Calculations were implemented in Python 3 using NumPy (eigen-decomposition and random sampling, seed 42). No human participants, animals, or personal data were involved.

3 RESULTS AND DISCUSSION

3.1 Criterion weights and consistency

Table 2 reports the weights derived from the specified pairwise matrices. Population or services served received the largest weight within criticality (0.418), and flood exposure received the largest weight within environmental vulnerability (0.455). At the top level, criticality (0.540) outweighed environmental vulnerability (0.297) and condition deficit (0.163). All three matrices were acceptably consistent, with CR values of 0.017, 0.004, and 0.008, well below the 0.10 threshold.

Table 2: AHP weights and consistency statistics for the illustrative judgements.

Level	Criterion	Weight	$\lambda_{\max}$	CI	CR
CSI criteria	C1 Population served	0.418	4.046	0.015	0.017
	C2 Redundancy deficit	0.223			
	C3 Interdependency	0.250			
	C4 Recovery time	0.110			
EVI criteria	E1 Flood exposure	0.455	4.010	0.003	0.004
	E2 Ground/erosion	0.141			
	E3 Land-use pressure	0.141			
	E4 Climate stress	0.263			
Top level	CSI	0.540	3.009	0.005	0.008
	EVI	0.297			
	ICD	0.163			

CI, consistency index; CR, consistency ratio; $\lambda_{\max}$, principal eigenvalue. Judgements are illustrative.

3.2 Index values and priority ranking

Table 3 and Figure 2 show the resulting indices. The water treatment plant had the highest IPI (0.757) and was the only Priority 1 asset, because it combined high criticality (CSI = 0.798) with high flood exposure (EVI = 0.714). The primary substation ranked second (IPI = 0.660); its criticality was the highest in the set (CSI = 0.812), but its lower environmental vulnerability kept it below the water plant. The transit hub (0.586) and the solid waste disposal site (0.586) were effectively tied for third place, differing by about 0.0003, and for different reasons: the transit hub through exposure, the waste site through a large condition deficit (ICD = 0.800). The telecommunications switching centre and the regional hospital fell into Priority 4.

Table 3: Dimension indices, Infrastructure Priority Index (IPI), rank, and priority class for the six hypothetical assets.

Asset	CSI	EVI	ICD	IPI	Rank	Class
Water treatment plant	0.798	0.714	0.700	0.757	1	Priority 1 (very high)
Primary substation	0.812	0.446	0.550	0.660	2	Priority 2 (high)
Transit hub	0.532	0.677	0.600	0.586	3	Priority 3 (medium)
Solid waste disposal site	0.457	0.704	0.800	0.586	4	Priority 3 (medium)
Telecom switching centre	0.702	0.376	0.350	0.548	5	Priority 4 (low)
Regional hospital	0.631	0.388	0.450	0.529	6	Priority 4 (low)

CSI, Criticality Score Index; EVI, Environmental Vulnerability Index; ICD, Infrastructure Condition Deficit. Synthetic data.

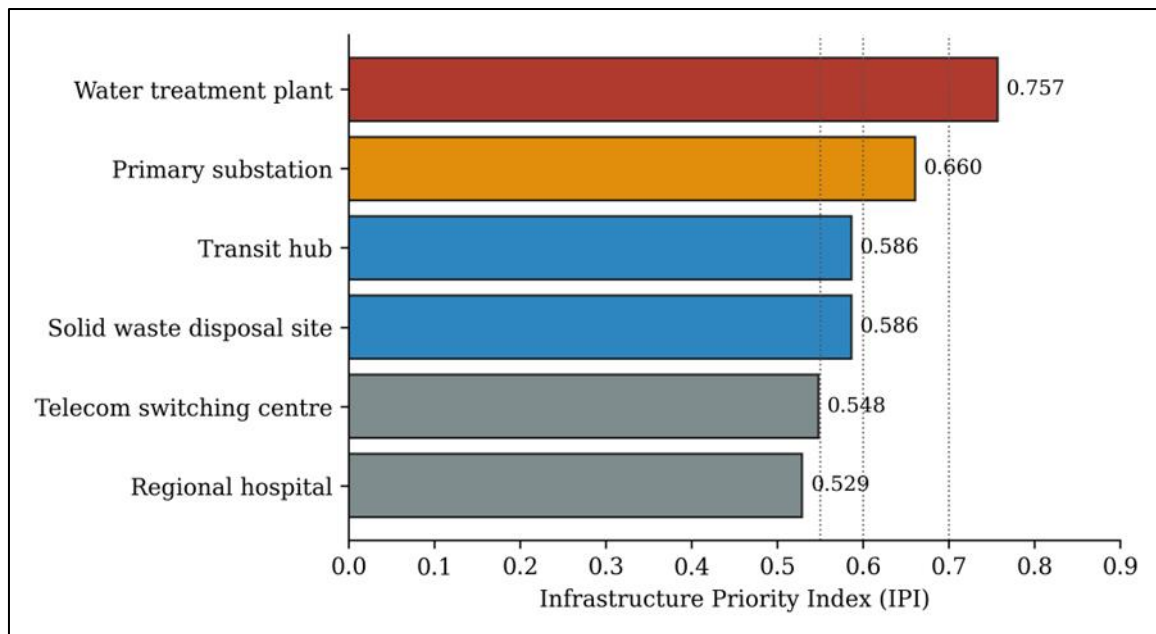


Figure 2: Infrastructure Priority Index of the six hypothetical assets. Dotted lines mark class thresholds (0.55, 0.60, 0.70).

3.3 Sensitivity analysis

Table 4 summarises the sensitivity tests. Varying any single top-level weight by $\pm 20\%$ changed only the relative order of the transit hub and the waste site; all other ranks were unchanged. In the Monte Carlo experiment the water treatment plant was ranked first in all 10,000 draws (probability = 1.00). The substation was ranked between 2 and 4 (mean 2.13), whereas the transit hub, waste site, and telecommunications centre showed wider rank ranges, and the hospital never rose above rank 4. The practical implication is that the top-ranked asset is robust to weight uncertainty, while the order of mid-ranked assets is not, and these are the assets for which better data or more careful expert elicitation would be most valuable.

Table 4: Rank stability under weight perturbation.

Asset	Base rank	Mean rank (MC)	Rank range (MC)	Rank range ($\pm 20\%$ OAT)
Water treatment plant	1	1.00	1	1
Primary substation	2	2.13	2–4	2
Transit hub	3	3.63	2–5	3–4
Solid waste disposal site	4	3.78	2–6	3–4
Telecom switching centre	5	4.64	3–6	5
Regional hospital	6	5.82	4–6	6

MC, Monte Carlo (10,000 Dirichlet draws, $\kappa = 30$); OAT, one-at-a-time perturbation of each top-level weight by $\pm 20\%$.

4 DISCUSSION

The demonstration shows that the framework produces a defensible, reproducible ranking from a small set of transparent judgements, and that it exposes which parts of the ranking are fragile. The use of AHP with consistency checking is consistent with its application to site selection and zoning problems in earlier Ghanaian studies [1,5,7], but here the same machinery is applied to existing assets rather than candidate sites, and three dimensions are combined rather than a single suitability surface.

Treating interdependency as a criterion links the framework to the network literature [10–12,15]. A substation or switching centre may serve a modest population directly yet support many other systems, and this is captured by C3 rather than by population alone. The inclusion of environmental indicators reflects the evidence, cited earlier, that environmental conditions and infrastructure interact in both directions [2,3,8,9]. In practical terms, flood exposure,

land-use pressure, and climate stress can be derived from the kinds of GIS and remote-sensing layers already used in hydrological and agro-ecological studies [2,7,8].

Several limitations should be stated plainly. First, the dataset is synthetic; the rankings demonstrate computation and do not describe any real facility. In particular, the low rank of the hospital follows from the values assigned here and should not be read as a statement about the relative importance of health services. In a real application, essential-service and social-vulnerability criteria should be considered explicitly, and the IPI should be understood as a tool for prioritising investment and protection, not for ranking social value. Second, AHP judgements are subjective; group elicitation, geometric-mean aggregation, and reporting of expert disagreement are needed. Third, weighted linear combination is compensatory and can mask an asset that is extreme on a single dimension; a screening rule or non-compensatory step may be added where this matters. Fourth, the interdependency score is a static count and does not simulate cascading failure or time-varying conditions, which approaches such as contingency analysis could address [11,12]. Finally, the class thresholds are arbitrary and need local calibration.

Future work should apply the framework to a real inventory, for example in a Nigerian municipal or state setting, with expert-elicited weights, field-verified indicators, and comparison against historical outage or damage records. Extensions to fuzzy or group AHP, dynamic weighting under climate scenarios, and explicit network simulation would strengthen the dependency component.

5 CONCLUSION

This paper presented a multi-criteria framework that unifies system criticality, environmental vulnerability, and infrastructure condition deficit into a single Infrastructure Priority Index, with AHP weighting, consistency checking, and two forms of sensitivity analysis. A synthetic demonstration showed that the procedure is simple to implement, that the top priority can be robust to weight uncertainty while mid-ranked assets are not, and that explicit reporting of rank stability can guide where additional data collection is most worthwhile. Because the demonstration is not based on field data, the immediate contribution is methodological. The framework offers a reproducible template that planners and researchers can populate with local indicators and expert judgements to support evidence-based infrastructure prioritisation under environmental risk.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

Disclosure of conflict of interest

The authors declare that they have no known financial or non-financial competing interests that could have influenced the work reported in this paper.

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