Optimizing Cyclone Shelter Allocation and Expansion in Teknaf Upazila

Riya Parikh, Ayela Chughtai, Rose Dana

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1 Introduction

1.1 Context and Motivation

Teknaf Upazila, located at the southernmost edge of Bangladesh along the Bay of Bengal, lies in one of the country's highest-risk cyclone corridors. Although a network of 161 cyclone shelters currently exists, the number of shelters is not sufficient relative to the population of 465,065 individuals, and their spatial distribution does not align well with where people currently live. Significant portions of the Upazila are located far from any existing facility, resulting in long travel distances and limited practical access during a cyclone. The Upazila's narrow geography, flood-prone coastline, and uneven terrain further limit evacuation options and create bottlenecks during extreme weather events. These mismatches between shelter supply and population demand highlight an urgent need to evaluate whether the current network provides adequate coverage and to identify where new shelters would most effectively improve safety.

1.2 Why This Problem Matters

Understanding and improving cyclone shelter accessibility in Teknaf is essential for reducing disaster-related casualties and ensuring equitable protection for all residents. In a region where evacuation time is limited and exposure levels vary sharply across short distances, identifying which areas are underserved, and by how much, is crucial for planning new shelter locations efficiently. By integrating population distribution, spatial risk variation, shelter capacities, travel distances, and geographical features, we can pinpoint high-demand areas with limited access, measure the population that remains uncovered under current infrastructure, and determine where additional shelters would yield the greatest reduction in risk and travel burden. Each kilometer of travel distance and each unit of shelter capacity materially affects who can reach safety. Optimization enables us to evaluate these constraints rigorously and design a shelter network that maximizes protection for high-risk residents during times of emergency while making efficient use of the limited infrastructure.

2 Data Description

We integrate demographic, geospatial, land-cover, topographic, and hazard-exposure datasets to construct a unified analytical grid for Teknaf Upazila. These processed datasets define the demand nodes, facility nodes, and spatial attributes required for our optimization model.

2.1 Existing Shelter Data

We obtained the initial list of cyclone shelters from the REACH Initiative and the District Relief and Rehabilitation Office (DRRO) Cyclone Shelter Dataset for Teknaf and Ukhiya Upazilas, hosted on the Humanitarian Data Exchange (HDX) platform. The raw dataset contains GPS coordinates, attribution fields, and descriptive metadata such as shelter capacity.
Data preprocessing steps included:

- restricting the dataset to shelters located within Teknaf Upazila,
- removing duplicate coordinates,
- restricting the analysis to mainland Teknaf and discarding offshore islands to ensure all modeled population nodes correspond to accessible land areas,

- snapping misaligned shelter points to the nearest mainland boundary using a 50–100 m tolerance,
- merging Teknaf Sadar and Teknaf entries, which refer to the same administrative area,
- filling missing capacity values using the maximum observed capacity in the dataset (a standard imputation approach when metadata is incomplete),
- verifying spatial consistency with union boundaries.

After cleaning, we retain **161 valid shelters**, which constitute the set of existing shelter nodes J_E in our optimization model.

2.2 Population Data

Teknaf Upazila consists of 11 unions (Baharchhara, Haldia Palong, Jalia Palong, Nhilla, Palong Khali, Raja Palong, Ratna Palong, Sabrang, Teknaf, Teknaf Paurashava, Whykong), each with distinct population sizes as recorded in the Bangladesh Bureau of Statistics (BBS) Population Census.
Union boundary shapefiles were obtained from the GADM (Global Administrative Areas Database). These boundaries serve as the spatial unit for later population disaggregation.

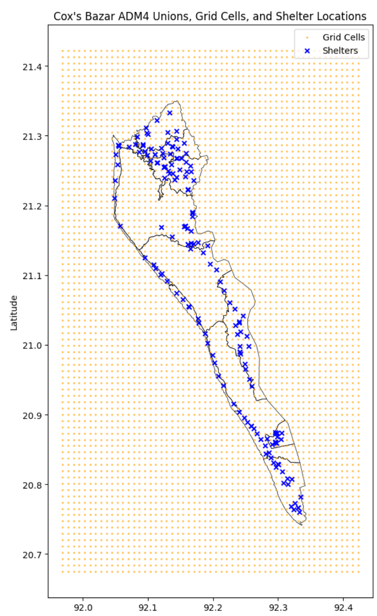

Figure 1: Union boundaries of Teknaf Upazila

To delimit the unions, we constructed a uniform $1\,\mathrm{km}^2$ grid covering the entire Upazila and overlay the grid with union boundaries. Intersecting the grid with the union polygons assigns each cell to exactly one union. The grid allows us to convert union-level population statistics into a distributed population surface, which defines the set of assignment nodes I for the optimization model and enables spatially explicit population allocation and shelter assignment.

To identify inhabitable land, we apply a series of geospatial filters. First, using the European Space Agency (ESA) WorldCover dataset, we remove grid cells classified as water or ice (though these are rare in Teknaf). Second, using Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data, we remove any cells above 40 m elevation or with slopes greater than 15 degrees, thresholds derived from National Oceanic and Atmospheric Administration (NOAA) cyclone flood-risk guidelines for delineating low-risk terrain. Because nearly all of Teknaf is low-lying and flat, this topographic filtering step also eliminates only a small number of elevated ridge cells.

The remaining cells represent feasible habitation zones. Population for each union is disaggregated by distributing the union's total population randomly across these inhabitable cells. This produces a distributed population surface reflecting the spatial footprint of settlement patterns.

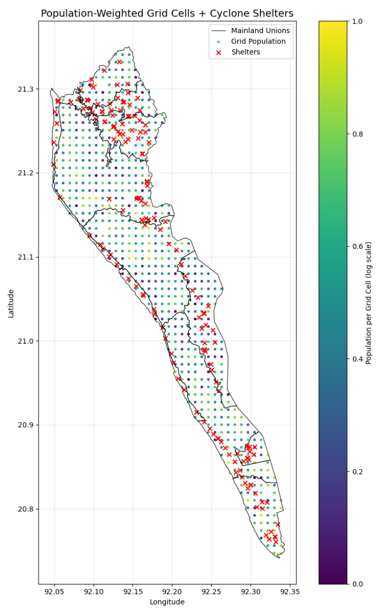

Figure 2: Populated $1\,\mathrm{km}^2$ grid cells after masking uninhabitable areas

To account for spatial vulnerability, each populated grid cell is enriched with environmental and cyclone-risk indicators: elevation (meters), slope (degrees), land-cover category, and distance to coastline (kilometers).

Because Teknaf is uniformly low-lying, elevation, slope, and land cover contribute minimally to relative risk. Instead, **proximity to the coastline is the dominant driver of hazard exposure**. We assign each grid cell a risk weight r_i based on its distance to the Bay of Bengal:

$$\begin{aligned} \text{Class 1 (highest risk):} \quad & < 1 \text{ km from coast} \\ \text{Class 2 (high risk):} \quad & 1\text{–}1.5 \text{ km} \\ \text{Class 3 (low risk):} \quad & 1.5\text{–}3 \text{ km} \\ \text{Class 4 (lowest risk):} \quad & > 3 \text{ km up to 6 km} \end{aligned}$$

These hazard classes align with national coastal risk zoning systems (Red Crescent coastal risk zones, UN OCHA flood depth models, Bangladesh Cyclone Preparedness Programme (CPP)) and support prioritizing shelter access for high-exposure populations.

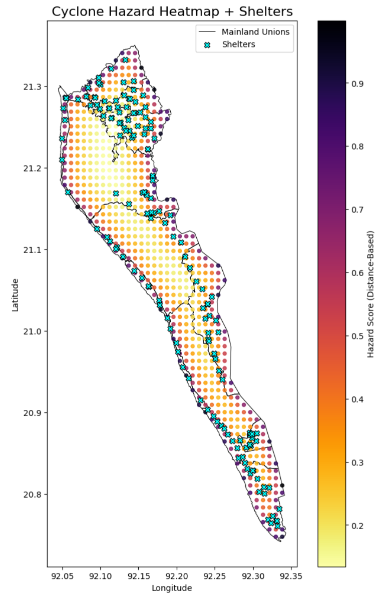

Figure 3: Cyclone Hazard Heatmap

For each grid cell i and each shelter j, we compute travel distances c_{ij} using the Haversine formula based on latitude–longitude coordinates and produce a complete distance matrix essential for computing distance-minimizing assignments in our optimization problem and enforcing maximum travel-distance constraints for the population.
This data processing allowed us to gather all the sets, indices, and parameters needed for our optimization problem.

3 Problem Formulation

The region is partitioned into 1 km^2 grid cells and each cell is treated as an assignment node. Fractional evacuation is allowed: each cell may send fractions of its population to multiple shelters. To obtain a Pareto-style frontier, we vary K, the maximum number of new shelters that may be opened. For each fixed K, we solve a lexicographically ordered three-stage problem:

1. **Stage 1 (Risk-coverage first):** maximize total risk-weighted covered population, producing $S_r^\star(K)$ and $\alpha_r^\star(K)$.
2. **Stage 1b (Existing-use tie-break):** among nearly Stage-1-optimal solutions, maximize use of existing shelters, producing $U_E^\star(K)$.
3. **Stage 2 (Distance tie-break):** among solutions preserving near-optimal risk coverage and existing-use, minimize total travel distance.

A hard travel cutoff $L_{\max}$ is enforced in all stages via a precomputed feasibility matrix.

Sets and Indices

- I: set of population cells (1 km^2), indexed by i.
- J_E: set of existing shelters.

- J_N: set of candidate new shelters.
- $J = J_E \cup J_N$: all shelters.

Parameters

- d_i: population in cell i.
- $r_i \geq 0$: cyclone-risk score of cell i.
- u_j: capacity of shelter j.
- c_{ij}: travel distance (Haversine) from cell i to shelter j.
- K: maximum number of new shelters allowed.
- $L_{\max}$: maximum allowed travel distance.
- $M_{ij} \in \{0,1\}$: feasibility indicator,

$$M_{ij} = \begin{cases} 1, & c_{ij} \leq L_{\max}, \\ 0, & c_{ij} > L_{\max}. \end{cases}$$

Total population and risk-weighted population are

$$D = \sum_{i \in I} d_i, \qquad R = \sum_{i \in I} r_i d_i.$$

Tolerance parameters:

$$\delta_{\text{frac}} > 0, \quad \delta_{S_r} = \delta_{\text{frac}} R, \quad \delta_{U_E} = \delta_{\text{frac}} D.$$

Decision Variables

- $x_{ij} \in [0,1]$: fraction of cell i assigned to shelter j.
- $y_j \in \{0,1\}$ for $j \in J_N$: $y_j = 1$ if a new shelter is opened.
- $y_j = 1$ for all $j \in J_E$ (existing shelters always open).

Risk-weighted covered population:

$$S_r(x) = \sum_{i \in I} \sum_{j \in J} r_i d_i x_{ij}.$$

Risk-weighted coverage fraction:

$$\alpha_r(x) = \frac{S_r(x)}{R}.$$

Raw coverage:

$$S(x) = \sum_{i,j} d_i x_{ij}, \qquad \alpha(x) = \frac{S(x)}{D}.$$

Existing-shelter utilization:

$$U_E(x) = \sum_{i \in I} \sum_{j \in J_E} d_i x_{ij}.$$

3.1 Stage 1: Maximize Risk-Weighted Coverage

$$\max_{x,y} \; S_r(x) = \sum_{i \in I} \sum_{j \in J} r_i d_i x_{ij}. \tag{S1-Obj}$$

s.t.:

$$\sum_{j \in J} x_{ij} \le 1 \qquad \forall i \in I \tag{S1-1}$$

$$\sum_{i \in I} d_i x_{ij} \le u_j y_j \qquad \forall j \in J \tag{S1-2}$$

$$\sum_{j \in J_N} y_j \le K \tag{S1-3}$$

$$x_{ij} \le M_{ij} y_j \qquad \forall i, j \tag{S1-4}$$

$$x_{ij} \in [0,1], \quad y_j \in \{0,1\} \; (j \in J_N), \quad y_j = 1 \; (j \in J_E) \tag{S1-5}$$

And let

$$S_r^\star(K) = \max S_r(x), \qquad \alpha_r^\star(K) = \frac{S_r^\star(K)}{R}. \tag{S1-Out}$$

3.2 Stage 1b: Maximize Existing-Shelter Use

$$\max_{x,y} \; U_E(x) = \sum_{i \in I} \sum_{j \in J_E} d_i x_{ij}. \tag{S1b-Obj}$$

s.t.:

$$\sum_{j \in J} x_{ij} \le 1 \qquad \forall i \tag{S1b-1}$$

$$\sum_{i \in I} d_i x_{ij} \le u_j y_j \qquad \forall j \tag{S1b-2}$$

$$\sum_{j \in J_N} y_j \le K \tag{S1b-3}$$

$$x_{ij} \le M_{ij} y_j \qquad \forall i, j \tag{S1b-4}$$

$$\sum_{i,j} r_i d_i x_{ij} \ge S_r^\star(K) - \delta_{S_r} \tag{S1b-5}$$

$$x_{ij} \in [0,1], \; y_j \in \{0,1\}, \; y_j = 1 \; (j \in J_E) \tag{S1b-6}$$

And let

$$U_E^\star(K) := \max U_E(x).$$

3.3 Stage 2: Minimize Distance

$$\min_{x,y} \; Z(x) = \sum_{i\in I}\sum_{j\in J} c_{ij} d_i x_{ij}. \tag{S2-Obj}$$

s.t.:

$$\sum_{j\in J} x_{ij} \le 1 \qquad \forall i \tag{S2-1}$$

$$\sum_{i} d_i x_{ij} \le u_j y_j \qquad \forall j \tag{S2-2}$$

$$\sum_{j\in J_N} y_j \le K \tag{S2-3}$$

$$x_{ij} \le M_{ij} y_j \qquad \forall i, j \tag{S2-4}$$

$$\sum_{i,j} r_i d_i x_{ij} \ge S_r^\star(K) - \delta_{S_r} \tag{S2-5}$$

$$\sum_{i\in I}\sum_{j\in J_E} d_i x_{ij} \ge U_E^\star(K) - \delta_{U_E} \tag{S2-6}$$

$$x_{ij} \in [0,1], \quad y_j \in \{0,1\}, \quad y_j = 1 \; (j \in J_E) \tag{S2-7}$$

Reported Outputs for Each K

Given the Stage-2 solution $(x^\star(K), y^\star(K))$, we report:

- Risk-weighted coverage:

$$S_r^{\text{real}}(K) = S_r(x^\star(K)), \qquad \alpha_r(K) = \frac{S_r^{\text{real}}(K)}{R}.$$

- Raw coverage:

$$S^{\text{real}}(K) = S(x^\star(K)), \qquad \alpha(K) = \frac{S^{\text{real}}(K)}{D}.$$

- Existing-shelter utilization:

$$U_E^{\text{real}}(K) = U_E(x^\star(K)).$$

- Minimum total distance:

$$Z^\star(K) = Z(x^\star(K)).$$

- Opened shelters $y^\star(K)$ and assignments $x^\star(K)$.

4 Results

4.1 Coverage Outcomes

After testing for different values of K ranging from 0 (no new shelters allowed) to 40 (maximum of 40 new shelters allowed), we found that an addition of 10, 20, and 40 shelters increases the risk-weighted coverage by 7.89%, 13.89%, and 23.53% respectively:

K	$\alpha_r^*(K)$	$\alpha^*(K)$
0	71.44%	53.39%
5	74.48%	56.08%
10	77.08%	58.77%
15	79.37%	61.46%
20	81.36%	64.14%
25	83.21%	66.83%
30	84.98%	69.52%
35	86.66%	72.21%
40	**88.25%**	**74.90%**

Table 1: Risk-weighted and raw population coverage given K

We obtain increasingly high coverage as K increases, as we allow for more shelters exactly where the population needs them. We plot the evolution of the risk-weighted coverage for each risk class 1 through 4 as K increases:

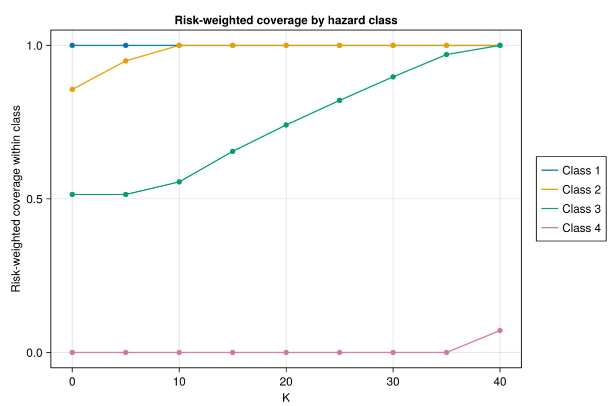

Figure 4: Evolution of coverage per risk class in terms of K

We can see here that risk-weighted coverage within each risk class increases as K increases, moving in order of risk severity. The current system leaves many residents exposed — only 71.4% are covered, and only Class 1 residents are fully protected. With 10 new shelters, coverage improves dramatically to 77.1% with both Class 1 and Class 2 populations fully protected. Additionally, more than half of Class 3 inhabitants are safe as well. With 20 shelters, we achieve 81% coverage and protect 75% of Class 3. And by 40 shelters, we reach complete coverage across all meaningful hazard groups, leaving only Class 4 residents uncovered (not an at-risk population). However, because Class 3 and 4 aren't considered endangered groups, the additional shelters required to fully protect them aren't worth the cost of creating these additional shelters. Thus, K = 10 is the realistic and cost-effective solution to this problem, as it balances high population coverage — especially for at-risk groups — and reasonable expansion of shelters.

4.2 Distance Minimization Outcomes

Our model also outputs the total distance traveled by inhabitants to shelters in an evacuation scenario for each K. From these results, we can see that an addition of 10, 20, and 40 shelters reduces the total distance traveled to shelters by 7.09%, 17.73%, and 38.79% respectively despite an increase in the number of travelers:

K	Total distance (km)
0	1.41M
5	1.34M
10	1.31M
15	1.26M
20	1.16M
25	1.07M
30	977k
35	935k
40	**863k**

Table 2: Total distance traveled to shelters given K

Moreover, we see that the total distance traveled by population to shelters decreases significantly as K increases. We plot the assignments of each grid cell to their allocated shelter:

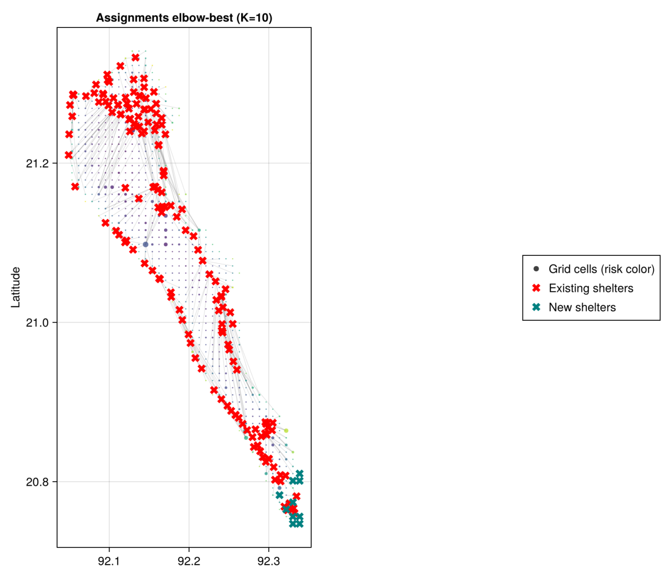

Figure 5: Assignment of cells to shelters for K*=10 additional shelters

We can see from this assignment map that, at our optimal $K^* = 10$, all 10 shelters are positioned at the southern tip of the region in the Sabrang Union. This implies that the Sabrang Union of Teknaf has a high population density but sparse shelter locations, essentially forcing populations to seek shelter further away. With 10 new shelters all located closely in that area, these local populations can now find shelters closer to their homes, greatly reducing their travel distance and the overall travel distances. Hence, these travel distances are further minimized as additional shelters are created to accommodate local communities.

5 Key Insights and Impact

Our results highlight several actionable implications for decision-makers in Teknaf. The spatial distribution of uncovered and high-risk cells shows that the most meaningful gains in protection come from the placement of new shelters at the southern tip of the Upazila in the Sabrang Union, where population density is high and existing shelter space has historically been too low.

For our optimal shelter expansion level of 10, we have manually identified real-life high-capacity infrastructures close to the locations of the new shelters in Teknaf that could feasibly be converted into shelters. These include, but are not limited to, the Baharchhara Union Parishad Complex, the IOM Teknaf Field Office, and the INSAF Hotel. The location correspondence between the model recommendations for shelter placement and the actual large buildings in Teknaf highlights the real-world applicability of our analysis and its potential to drive a realistic and meaningful impact in the region.

6 Conclusion

6.1 Main Takeaways

Our analysis demonstrates that the accessibility of cyclone shelters in Teknaf Upazila is currently insufficient, both in terms of coverage and proximity. By integrating population, risk, and shelter capacity information into a unified spatial optimization model, we were able to identify where under-service exists and how additional shelters can improve protection, especially for high-risk coastal populations. Risk-based prioritization is essential: expanding the network by only 10 shelters substantially increases overall coverage while ensuring that all high-risk residents gain access to safety. Beyond this point, additional shelters produce diminishing returns, especially for lower-risk areas. In general, the study provides a scalable framework that identifies where shelter investment is most impactful and how minimal resources can be allocated to maximize community protection.

6.2 If We Had Another Week

If additional time were available, several meaningful extensions could enhance the realism and policy relevance of our analysis. A natural next step would be to incorporate a road-network model to replace straight-line distances with shortest-path travel times, allowing us to capture the practical constraints of evacuation under real transportation conditions. Another improvement would involve adding simple constraints based on shelter quality or structural condition, ensuring that only facilities that meet basic safety standards are considered viable in the optimization. These extensions would allow the model to further reflect the real-life challenges faced in Teknaf Upazila.

References

Humanitarian Data Exchange. (2024). *Cox's Bazar District: Teknaf and Ukhiya Upazila Cyclone Shelter Locations*. https://data.humdata.org/dataset/cox-s-bazar-district-teknaf-and-ukhiya-upazila-cyclone-shelter-locations.

Banglapedia: Teknaf Upazila https://en.banglapedia.org/index.php/Teknaf_Upazila

Banglapedia: Upazilas of Bangladesh https://en.banglapedia.org/index.php?title=Category:Upazilas_of_Bangladesh

Bangladesh Bureau of Statistics (BBS) – Population Census 2011 (Teknaf report, PDF) https://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/86b66335_4fa7_4143_a034_9abe3c537553/2020-05-15-16-23-ebfd02cda263d2cb76f4e75b1c7f91cc.pdf

GADM Global Administrative Boundaries https://gadm.org/download_country.html

HDX: Teknaf & Ukhiya Cyclone Shelters https://data.humdata.org/dataset/cox-s-bazar-district-teknaf-and-ukhiya-upazila-cyclone-shelter-locations

GADM auxiliary raster layers https://gadm.org/download_country.html

USGS EarthExplorer https://earthexplorer.usgs.gov

USGS Data Catalog https://data.usgs.gov/datacatalog/data/USGS:60a81500d34ea221ce4e5a6d

HDX: Bangladesh Natural Hazard Datasets https://data.humdata.org/dataset/bangladesh-natural-hazards-datasets

UNDRR (2020). *Bangladesh Disaster Risk Landscape*. https://www.undrr.org/publication/bangladesh-disaster-risk-landscape

World Bank GFDRR (2017). *Bangladesh Disaster Risk Profile*. https://www.gfdrr.org/en/publication/bangladesh-disaster-risk-profile

IPCC AR6 WG2 (2022). *Impacts, Adaptation and Vulnerability*. https://www.ipcc.ch/report/ar6/wg2/

BWDB (2021). *Coastal Flood Risk Atlas of Bangladesh*. (Report—no stable public URL available)

UN OCHA (2018). *Cox's Bazar Coastal Hazard Profile*. https://data.humdata.org

UNDP (2019). *Coastal Vulnerability Assessment for Bangladesh*. (Report—no stable public URL available)

Geological Survey of Bangladesh (2019). *Landslide Hazard Zonation Map: Cox's Bazar District*. (Technical map—no stable public URL available)

Bangladesh Meteorological Department (BMD) (2017). *Cyclone Risk Map of Bangladesh*. (Printed atlas and GIS product)