SPATIAL ANALYSIS OF DISASTER LOGISTICS IN SLOVENIA: A CASE STUDY OF CELJE AND THE 2023 FLOODS

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Abstract

Abstract As a result of climate change, the increase in the frequency and intensity of hydrometeorological disasters necessitates a reassessment of traditional disaster management strategies and logistical planning. Slovenia's geographical and hydrogeological structure, combined with the flood disaster that occurred in August 2023, has pushed the limits of the existing civil protection infrastructure. This research presents a spatial analysis of a two-echelon distribution network design for humanitarian aid logistics in the context of Slovenia's multi-hazard profile. The study focuses on the Thiessen Polygons (Voronoi Diagrams) analysis, a direct GIS-based geometric solution method, and validates the results with the Set Covering Problem (SCP), a mathematical optimization model, to ensure network resilience. The report is based on the manual identification of potential logistics depot locations in the Celje region. The resulting geometric service areas were overlaid with flood risk maps to analyze accessibility constraints.

1. INTRODUCTION

Background and Significance of the Study

Humanitarian aid logistics differs fundamentally from commercial supply chain management: the objective is not to maximize profit, but to alleviate human suffering and prevent loss of life. The first 72 hours of a disaster, known as the "golden hours," are critical for delivering essential supplies (Rawls & Turnquist, 2010; Balcik & Beamon, 2008). However, disasters often destroy the very transportation infrastructure required for this delivery. Due to its location at the intersection of Alpine, Dinaric, Pannonian, and Mediterranean climates, Slovenia is highly vulnerable to hydrometeorological risks (IFRC, 2024).

Traditional facility location models typically minimize cost or maximize coverage under the assumption of a functional network. However, the August 2023 floods in Slovenia demonstrated the fragility of this assumption. The collapse of major arteries and the isolation of settlements in the Savinja Valley highlighted the urgent need to prioritize "resilience" over "efficiency" in logistics planning (WTW, 2023).

Problem Definition: Slovenia's Disaster Profile

While Slovenia must adopt an "all-hazards" approach, the most destructive logistical scenarios are those that physically disrupt the transportation network.

Flood Risk and the August 2023 Disaster

The August 2023 floods were the most costly natural disaster in Slovenia's history, with damages estimated at €9.9 billion (Bezak et al., 2023). Hydrologically, this event provided critical lessons for logistics:

Preliminary Conditions: The first half of 2023 was exceptionally rainy, and by July, the soil was saturated and had lost its water retention capacity.

Meteorological Bomb: Mediterranean and Adriatic sea water temperatures were 2°C above average, increasing atmospheric instability and resulting in rainfall exceeding 200 mm within 12 hours between August 3 and 6 .

Infrastructural Collapse: This extreme rainfall not only caused rivers to overflow but also triggered large-scale landslides and morphological changes in riverbeds. The collapse of bridges over the Savinja River and the flooding of roads brought logistical operations in regional centers like Celje to a standstill.

Table 1: Critical Infrastructure Damage in the August 2023 Floods

Logistics Blind Spots

Existing civil protection warehouses and commercial logistics centers (e.g., Intereuropa, Pošta Slovenije) are traditionally located near highway networks on flat terrain for economic efficiency (Intereuropa, 2024). However, in the Celje basin, these "flat terrains" correspond to floodplains. A systemic vulnerability exists where either the depots themselves or the roads connecting them to demand points are located in high-risk zones.

Purpose and Scope of the Study

This research aims to visualize and quantify this vulnerability using Geographic Information Systems (GIS) and mathematical optimization. The study specifically addresses the following research question: How resilient are service areas created through Thiessen polygons when overlaid with flood risk maps? The methodology involves: (1) Manual identification of potential depots in Celje;

(2) Generating theoretical service areas using Voronoi diagrams; (3) Analyzing accessibility constraints by overlaying Q100 flood maps; and (4) Validating the results using a Set Covering Problem (SCP) algorithm.

Literature Review: Site Selection and GIS in Humanitarian Aid Logistics

This section examines the academic literature that forms the theoretical basis of the study, particularly in the context of hierarchical site selection, the use of Voronoi diagrams, and disaster logistics.

Hierarchical Models in Humanitarian Aid Logistics (HFLM)

Humanitarian supply chains, unlike commercial chains, are characterized by uncertainty, high demand fluctuations, and infrastructure damage. To overcome these challenges, Two-Echelon or Hierarchical Facility Location Models (HFLM) are frequently proposed. These models typically consist of two levels: strategic Main Distribution Centers (MDC), which are permanent facilities located near international entry points (Rawls & Turnquist, 2010), and operational Local Distribution Centers (LDC), which are flexible structures positioned closer to the disaster area. Yilmaz and Kabak (2024) demonstrated that the simultaneous optimization of these two levels significantly shortens the response time. In flood scenarios, these local warehouses must be capable of autonomous operation when cut off from the main network.

Spatial Analysis and Voronoi Diagrams

Voronoi diagrams (Thiessen polygons) partition a plane into regions based on the nearest neighbor principle. Boonmee et al. (2017) highlight that

Voronoi diagrams are ideal for rapidly defining a "catchment area" without requiring complex network data, particularly in the initial chaotic phase of a disaster. However, a major limitation is that they rely on Euclidean (bird's-eye) distance. In mountainous regions like Slovenia, a short Euclidean distance may correspond to a long or impossible travel route due to terrain (ArcGIS Pro Documentation, 2024). This study utilizes this limitation as an analytical tool: by identifying where flood barriers intersect idealized polygons, the "bottlenecks" in the system are revealed.

Logistics Lessons Learned from the 2023 Flood

Field reports from the August 2023 disaster document the devastating impact on logistics infrastructure. Bezak et al. (2023) noted that the floods reached 500-year recurrence intervals, causing significant damage. The most critical finding for logistics was the vulnerability of river crossings; the collapse of bridges in the Savinja Valley isolated upstream settlements such as Luče and Solčava for days (ReliefWeb, 2023). This demonstrates that "accessibility reliability" is a more critical parameter than geometric proximity in facility location selection.

Methodology: Spatial Analysis with GIS

3.1. Data Acquisition and Preparation

The success of any GIS analysis depends on the quality of the spatial data. This study utilizes three primary datasets to model the logistics network in Celje:

Potential Facility Locations (Point Data): Existing logistics centers (e.g., Intereuropa, Pošta Slovenije) and safe public structures (e.g., Zlatorog Hall) were manually identified based on atlas data and local topography. These points represent candidate Main Distribution Centers (MDCs).

Demand Points/Risk Zones (Point Data): High-density residential areas and critical infrastructure points in the Celje basin were mapped as demand locations where humanitarian aid would be required.

Hydrological Data (Flood Risk): The Q100 (100-year return period) flood spread maps, provided by the Slovenian

Environment Agency (ARSO) and Copernicus EMS, were used to represent the physical barriers affecting the network (European Commission, 2023).

Data Visualization with Python (Folium)

Before applying complex spatial algorithms, the distribution of risk zones (8 points) and potential depots (4 points) was visualized to understand the spatial context. The Python programming language and the 'Folium' library were employed to generate an interactive map layout (Python Software Foundation, n.d.). This step allowed for a preliminary assessment of the physical distribution of points on a satellite map.

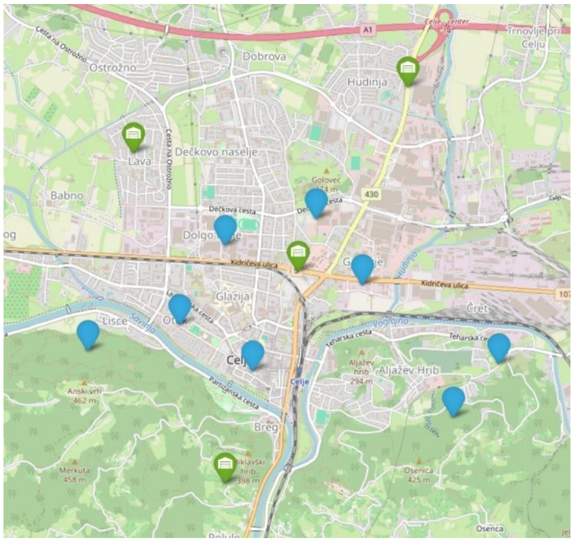

Figure 1: Interactive Location Map created with Python (Folium), showing risk zones (blue) and potential depot locations (green).

Creating Thiessen Polygons (Voronoi Diagrams)

The delineation of service areas was performed using the "Create Thiessen Polygons" tool within the Analysis toolbox of ArcGIS Pro. This geometric approach, mathematically known as Voronoi tessellation, partitions the study area into regions based on the nearest-neighbor principle. Consequently, any location within a generated polygon is closer to the associated depot than to any other facility in the network.

A critical technical step in this process was the definition of the spatial reference system. Given that the analysis relies heavily on Euclidean distance calculations, the project was strictly defined using the D96/TM (Slovenian National Grid) projected coordinate system. Using a geographic coordinate system like WGS84 would introduce significant distortions in area and distance measurements, leading to inaccurate service boundaries.

Furthermore, to ensure the analysis remained relevant to the administrative and operational scope, the "Processing Extent" environment setting was constrained to the Celje municipality boundary. This prevented the generation of infinite polygons at the outer edges of the point set (convex hull). The resulting vector layer represents the theoretical "dominance area" of each manually selected depot. For visualization purposes, these polygons were rendered with 50% transparency to allow for the simultaneous assessment of underlying topographic features and flood risk zones.

Flood Risk Overlay Analysis

Thiessen polygons alone only indicate geometric proximity based on a barrier-free surface. To assess the "resilience" of the proposed network, a critical overlay analysis was performed by integrating hydrological data into the GIS environment.

The process involved superimposing the Q100 (100-year return period) flood risk map and the August 2023 event map onto the generated Thiessen layer. This visual intersection analysis aimed to answer a critical research question: Does the flood hazard affect the facility location itself (point) or the accessibility of its service area (polygon)? The study identified two distinct failure scenarios:

Scenario A (Depot Inundation): If the point coordinate representing a candidate depot falls directly within the flood layer, the facility is deemed non-operational. Consequently, the entire associated Thiessen polygon is considered "offline," creating a significant service gap in the logistics network.

Scenario B (Access Interruption): A more complex failure occurs when the depot itself is located in a dry zone, but the floodwaters (e.g., the overflowing Savinja River) intersect the polygon between the depot and its assigned demand points. In this case, the Thiessen polygon loses its validity; although the Euclidean distance suggests proximity, the actual physical access is severed, rendering the service area inaccessible.

Verification of Manual via GIS

The final stage of the methodology involved a GIS- based verification of the manually selected potential depot locations. The manual selection, initially based on expert judgment and atlas data, was rigorously tested against the spatial analysis results:

Risk Assessment: Any manually selected storage facility that was found to be located within the Q100 floodplain during the overlay analysis was flagged as "high risk" and eliminated from the candidate list.

Capacity and Coverage Check: If a selected storage facility was confirmed to be in a safe zone but its resulting Thiessen polygon covered an excessively large geographic area (indicating a potential capacity overload or excessive travel time), the analysis concluded that an additional Local Distribution Center (LDC) must be established within that specific sector to ensure adequate coverage.

Case Study: Celje and the Savinja Valley

This section presents the results of the spatial analysis applied to the Celje region, incorporating data from the August 2023 flood disaster to validate the theoretical models.

Characteristics of the Region and Its Logistical Importance

Celje, Slovenia's third-largest city, is strategically located at the confluence of the Savinja and Voglajna rivers. While this location makes it a vital logistics hub, it also creates a significant hydrological vulnerability. During the August 2023 floods, the overflowing Savinja River caused extensive damage to the northern and western districts, severing connections towards Laško and the Upper Savinja Valley (ReliefWeb, 2023). The riverbed, which runs directly through the urban center, has a wide floodplain that inundates low- lying settlements and logistics zones during extreme events.

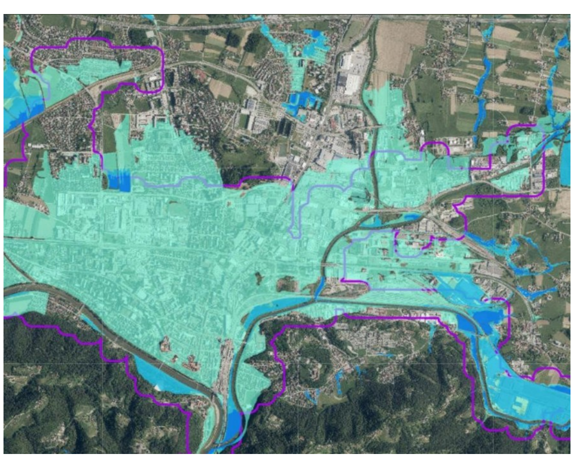

Figure 2: The floodplain of the Savinja River in Celje. The blue areas represent high-risk zones (Q100) where logistics operations would be compromised.

Analysis of the Thiessen Polygon Map

The Thiessen polygon analysis was applied to four manually selected candidate depots to determine their geometric service areas. The resulting map

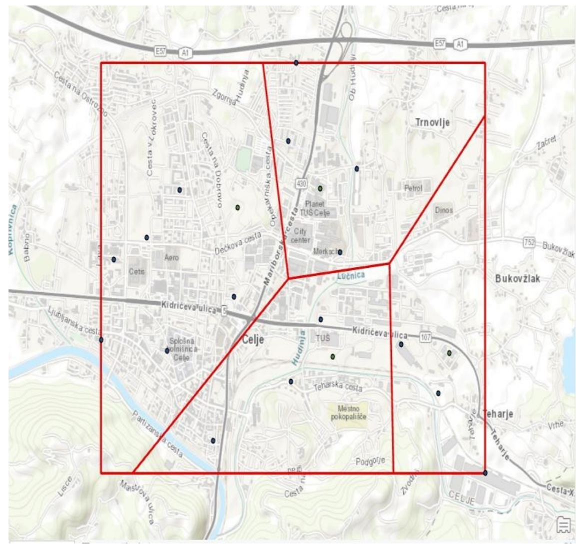

Figure 3: Proposed warehouse locations and their geometric service areas (Thiessen Polygons).

reveals the "dominance area" of each depot based on Euclidean distance.

The areas separated by red lines show the service areas of the selected storage points.

Observation 1: The boundaries of the polygons generally do not coincide with physical barriers such as rivers or main roads (a natural result of the Thiessen method). The boundaries are purely mathematical midpoints.

Risk Identification: For example, a depot on the left bank of a river may appear to serve a neighborhood on the right bank according to Thiessen boundaries. However, if the flood map (Figure 2) shows that bridges over the river are at risk or submerged, the neighborhood on the right bank becomes “unserved.”

Conflict: If some depots in the center of Celje are observed to be very close to or within the dark blue (deep water/high velocity) areas on the flood risk map, selecting these depots as "Main Depots" (MDC) is a strategic error. These points can only be used during "temporary, low-risk periods."

Lessons Learned from the 2023 Flood and Model Validation

In August 2023, many bridges were destroyed and roads were closed in the Savinja Valley.

Logistical Disruption: Road connections between Celje and upstream towns such as Mozirje, Ljubno, and Luče were severed. Thiessen analysis may "geometrically" show that a depot in Celje could serve these areas, but "topologically" this has become impossible.

The example of Črna na Koroškem: This town in the Meža Valley was isolated for days. This situation demonstrates that LDCs (local distribution centers) should be located not only for logistical efficiency (cost) but also to provide "autonomy." Every basin at risk of isolation should have its own self-sufficient LDC.

Mathematical Verification: Set Covering Problem (SCP)

In the previous sections, we determined the service areas geometrically using Voronoi diagrams. However, we also wanted to verify these locations mathematically. Therefore, we adapted the 'Set Covering Problem' algorithm from our previous facility planning projects to the Celje case (Kolen & Tamir, 1987).

We used Python to calculate the minimum number of depots needed. We defined a 3.5 km service radius (R) for emergency vehicles because road conditions are difficult during floods.

The logic of the algorithm is simple:

We created a binary matrix (0 and 1).

If a depot is within 3.5 km of a risk point, the value is 1. If not, it is 0.

The code tests all combinations to find the best solution.

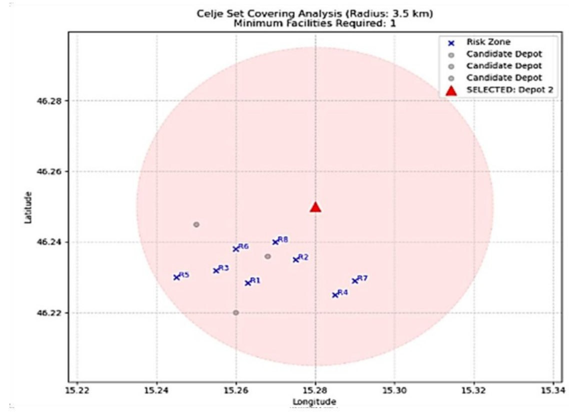

Figure 4: Mathematical validation result using Set Covering Problem (SCP).

Results: The Python analysis with a 3.5 km radius indicated that mathematically, a single strategic depot (Depot 2) is sufficient to cover all risk zones geometrically. However, relying on a single depot creates a single point of failure. Therefore, while the algorithm proves the high coverage efficiency of the northern region, our proposed multi-depot system (Figure 3) is maintained to ensure redundancy and resilience against potential bridge collapses.

Discussion: Beyond Euclidean Distance

The Thiessen (Voronoi) approach used in this study serves as a powerful visual tool for the initial "rapid assessment" phase of disaster management. However, the application of this geometric method in a topography as complex as Slovenia reveals significant limitations that must be addressed in future planning.

Geometric Proximity vs. Network Access

In mountainous countries such as Slovenia, Euclidean ("as the crow flies") distances are often misleading. Two points may appear adjacent on a map, yet be separated by a mountain range or a river requiring a detour of several kilometers. Thiessen polygons, by definition, ignore these geographical barriers. While future research

should incorporate the Network Analyst module in ArcGIS to calculate travel times based on the actual road network, Thiessen polygons remain a valid reference for the "baseline" scenario, particularly when the road network status is unknown or highly dynamic during the first hours of a crisis (ArcGIS Pro Documentation, 2024).

The Effect of Flood Barriers

Floods act as a "dynamic barrier" on the logistics network. As water levels rise, passable routes decrease non-linearly. A critical finding of this study is that flood resilience cannot be determined solely by the location of the facility. Even if a selected warehouse is located outside the Q500 (500-year return period) flood zone, it is rendered useless if its "exit routes" are submerged. Thiessen analysis partitions the area but does not account for connectivity. Therefore, manual verification is essential to determine whether the boundaries of a service area coincide with a river, implying a reliance on vulnerable bridges.

2. CONCLUSION

Slovenia's complex topography and increasing exposure to climate-induced risks necessitate a paradigm shift in disaster logistics: moving from static, cost-oriented planning to dynamic and resilient network design. This study presented a GIS-based optimization approach validated by infrastructure damage data from the August 2023 floods.

The spatial analysis revealed that while geometric models (Thiessen polygons) can efficiently partition service areas, they often fail to account for physical accessibility constraints. Overlaying these models with flood risk maps demonstrated that many theoretically "optimal" depot locations could become inaccessible due to bridge collapses, particularly in the Celje and Savinja regions.

Consequently, humanitarian logistics networks in flood-prone regions must be designed with redundancy. Relying on a single central depot—even if mathematically sufficient—creates a single point of failure. The proposed multi-depot system, while more costly, ensures that relief operations can continue even if primary transportation corridors are severed. The methodology and technical workflow presented in this report provide a scalable framework for future academic and practical studies aimed at enhancing disaster resilience.

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