Optimizing Geo-governance and Resilience to Industrial Risks through Spatial Modeling: The Case of Sétif (North east Algeria)

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Abstract

This article proposes and validates an integrated methodological framework designed to transform urban vulnerability diagnostics into an operational spatial decision-making tool, which is essential for Geo-governance and strengthening resilience against major industrial risks. The study focuses on the city of Sétif (Algeria), where rapid urban sprawl has created a critical spatial confrontation between the industrial zone and residential assets.

The methodology relies on the functional integration of systemic hazard analysis via the MADS Model (*Modèle d'Analyse des Dysfonctionnements du Système*) within a GIS environment. The MADS formalism (Source $\rightarrow$ Flow $\rightarrow$ Target) was translated into a structured Geodatabase (GDB), serving as a single information repository for multi-stakeholder coordination. The efficiency of the emergency response is quantified using the ArcGIS Network Analyst extension, applied to optimize rescue and evacuation routes in simulated crisis scenarios.

The findings demonstrate that the MADS-GIS approach yields measurable and significant efficiency gains. Optimizing rescue routes resulted in a response time reduction of approximately 33% (dropping from 12 to 8 minutes). Concurrently, optimized evacuation routes achieved a time saving of up to 28%.

The study concludes that Geo-governance, when supported by the integration of the systemic MADS model and spatial optimization tools, is the key to converting vulnerability diagnosis into a measurable and adaptable response capacity. This framework provides Sétif authorities with a strategic lever to minimize impact and ensure the continuity of critical urban functions during a crisis.

Keywords; Sétif, Geo-governance, Resilience, Industrial Risk, GIS, MADS, Network Analyst

1.Introduction

The uncontrolled and rapid urbanization represents one of the major challenges of the 21st century for urban planning, particularly in developing countries. In Algeria, urban sprawl continues to concentrate populations in the northern region, historically the most exposed to major risks (CNES, 2003; MATE, 2003). This phenomenon, exacerbated by occasionally ineffective urban planning, has led to a dangerous juxtaposition of residential areas and high-risk industrial sites, structurally increasing the vulnerability of populations (Kadri et al., 2013). In the city of Sétif, this urban sprawl dynamic has brought the urban area closer to the historical industrial zone, placing entire neighborhoods within the danger perimeters.

Faced with these complex threats, simple risk analysis (identifying danger sources and modeling consequences) is insufficient. The priority shifts toward the concept of urban resilience, defined as the capacity of an urban system to maintain its basic functions and recover quickly after a disruptive event (Longley & Mesev, 2006; Tolly et al., 2015). The complexity of this task lies in the coordination of multiple stakeholders (rescue services, local authorities, industrialists) and rapid, informed decision-making, which falls within the scope of Risk Governance.

When this governance is equipped with geographic information to optimize spatial decision-making, it is referred to as Geo-governance (Senior et al, 2008). Geo-governance thus requires the integration of spatial and decisional dimensions to optimize resource management and emergency operations, ensuring the continuity of the city's critical functions.

Previous work has extensively documented the spatial vulnerability of cities. A recent study on Sétif, conducted by Melal et al. (2024) used remote sensing and ALOHA software to quantify and spatially materialize the consequences of urban sprawl on assets. The main result of this article established a critical diagnosis: the superposition of industrial risk thermal effect perimeters and urbanized areas in Sétif, posing a major challenge to resilience.

However, a methodological gap remains: the operational articulation of analytical tools (notably the systemic hazard model MADS—*Modèle d'Analyse des Dysfonctionnements du Système*—which was conceptually introduced) within a Geo-governance decision-making framework is underexplored. This present work is positioned as the logical and operational continuation of that analysis, aiming to transform the vulnerability diagnosis into a concrete spatial decision support tool. The objective is to demonstrate how structured and modeled data can be used to optimize the operational response and thus enhance urban resilience.

This article aims to fill this gap by developing and demonstrating an integrated framework for spatial decision support, centered on the Geo-governance of industrial risks. The specific objectives are:

To demonstrate the functional integration of the conceptual MADS model into the design of an operational Geodatabase, using ArcGIS Diagrammer to structure the data necessary for risk management (Parent et al., 2006).

To operationalize resilience concepts using the ArcGIS Network Analyst extension to model and optimize intervention and evacuation routes in a crisis situation, thereby measuring the efficiency of the emergency response (Wang & Meng, 2007).

To evaluate how this integrated GIS-MADS system can serve as a foundation for Geo-governance by facilitating multi-stakeholder collaboration and providing a proven spatial information base for rapid decision-making.

The work is structured as follows: Section 2 presents the methodological framework based on data modeling (CDM/LDM) and network analysis. Section 3 details the results of route optimization in Sétif and their implications for response times. Finally, Section 4 discusses the implications for urban Geo-governance and resilience.

2.Materials and Methods

2.1. Study Area Presentation

The study area is the city of Sétif, located in the heart of the Algerian High Plateaus 36°11′ N et 5°24′ E The agglomeration is a major demographic center, hosting over 400,000 inhabitants (ONS, 2023).

The choice of Sétif as a case study for the Geo-governance of industrial risks is justified by the convergence of several critical factors (Longley et al, 2006):

Sétif's urban history, marked by rapid and uncontrolled urban sprawl since the 1970s, has led to a dangerous juxtaposition between the industrial zone (ZI of 282 hectares, including electrochemical/plastic industries) and residential areas. Our previous work (Melal et al., 2024) proved that the urban space now reaches the effect perimeters (thermal/blast) of dangerous sites.

This critical vulnerability necessitates an urgent shift from diagnosis to action. The study uses the Sétif case to test and validate an operational framework for Geo-governance capable of providing optimal intervention and evacuation routes in a crisis situation (Senior et al, 2008).

The case of Sétif thus represents an emblematic situation for medium-sized cities in North Africa, where integrating risk management upstream of urban planning has become essential for resilience.

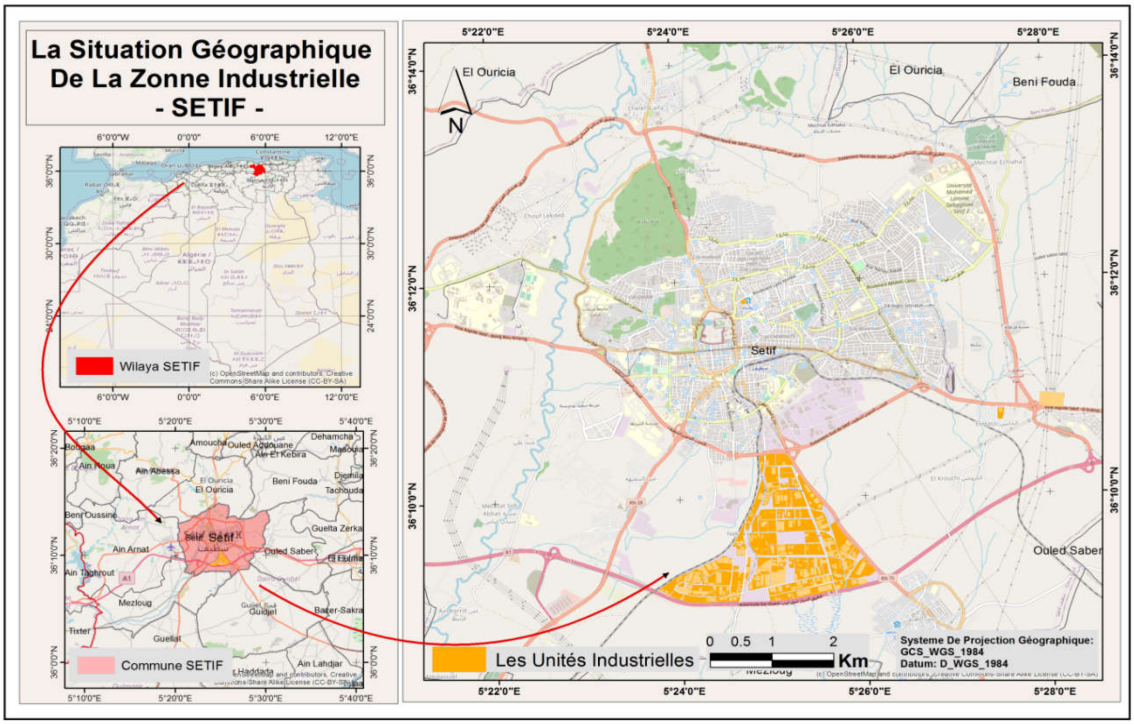

Figure 1: Presentation of the Industrial Zone of Sétif City.
Source: Author's own creation, using ArcGIS

2.2. Methodological Approach: From Systemic Analysis (MADS) to Spatial Decision Support (GIS)

Our methodology is based on an integrated approach that structures risk analysis (via the MADS model) within a spatial decision support environment (GIS), with the aim of optimizing disaster management.

2.2.1. Integration of the MADS Model and the Geodatabase

The study relies on the conceptual MADS Model (*Modèle d'Analyse des Dysfonctionnements du Système*) for the systemic analysis of the industrial hazard process. This model allows the phenomenon to be broken down into a fundamental triplet relationship: Source of Hazard Hazard Flow Target (Asset) (Laurent et al., 2017). The use of MADS ensures that the modeling is not limited to physical entities but encompasses the critical relationships that define the risk.

This systemic approach was directly translated into the process of designing the geographic database:

Conceptual Data Modeling (CDM): The Entity-Relationship (ER) structure was developed to represent real-world entities (e.g., industrial facilities, road segments, hospitals, residential areas) and their spatial and functional relationships, in accordance with the MADS formalism (Parent et al., 2006). This CDM was designed and validated using ArcGIS Diagrammer.

Validation and Transformation: The validation of the CDM, including the verification of syntactic coherence and functional completeness (Caloz, R.), preceded its transformation.

Exporting the schema in XML format allowed its importation into ArcCatalog to generate the Geodatabase (GDB).

Transition to the Logical Data Model (LDM): The transformation of the CDM into the LDM allowed the entities to be materialized into tables, identifiers into primary keys, and associations into foreign keys, thus guaranteeing the integrity and structuring of the data within the Database Management System (DBMS) (Ph Chochois). This structured database serves as a unique and reliable informational foundation for Geo-governance.

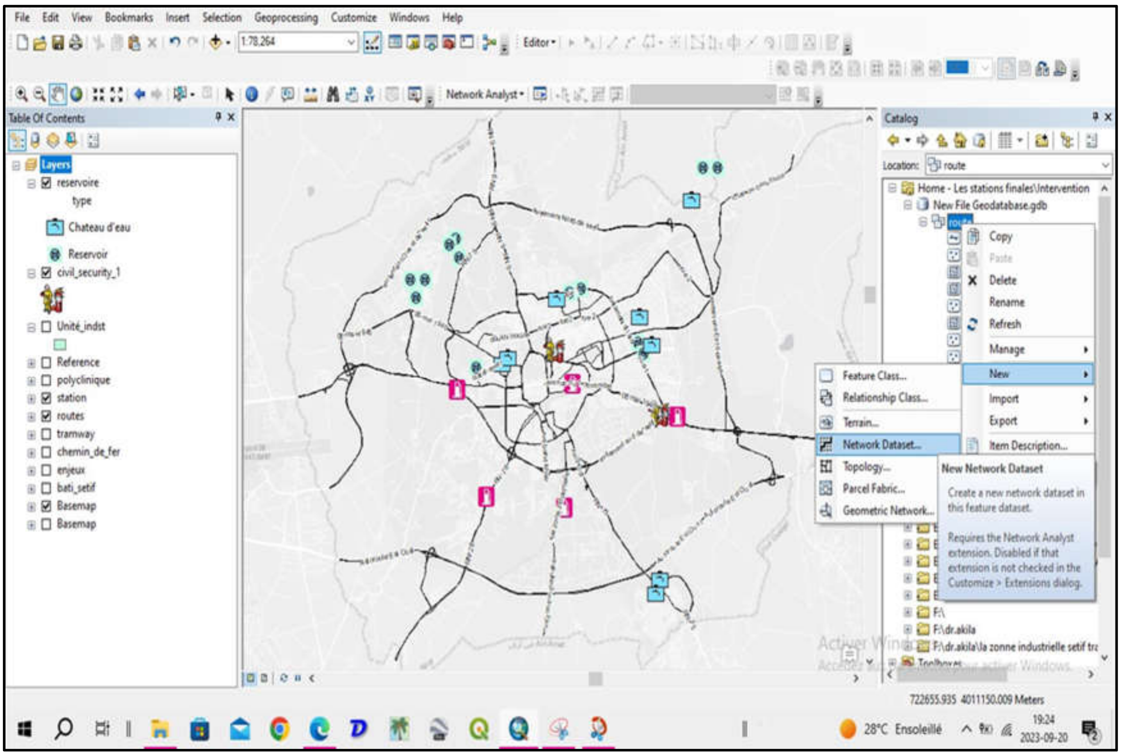

Figure 2 *: Configuration of the Network Analyst Environment.*

Source: Author's own creation, using ArcGIS

2.2.2. Operational Spatial Modeling for Resilience

The optimization of the emergency response, a core pillar of urban resilience, was achieved through **network analysis**.

Construction of the Geometric Network: The Geodatabase was used to build a faithful geometric network of the city of Sétif (Longley et al, 2006). This network is composed of edges (roads and paths, modeled as lines) and junctions (intersections, modeled as points). This physical network generated the abstract logical network (composed of nodes and directed arcs), which is essential for calculating flows and costs.

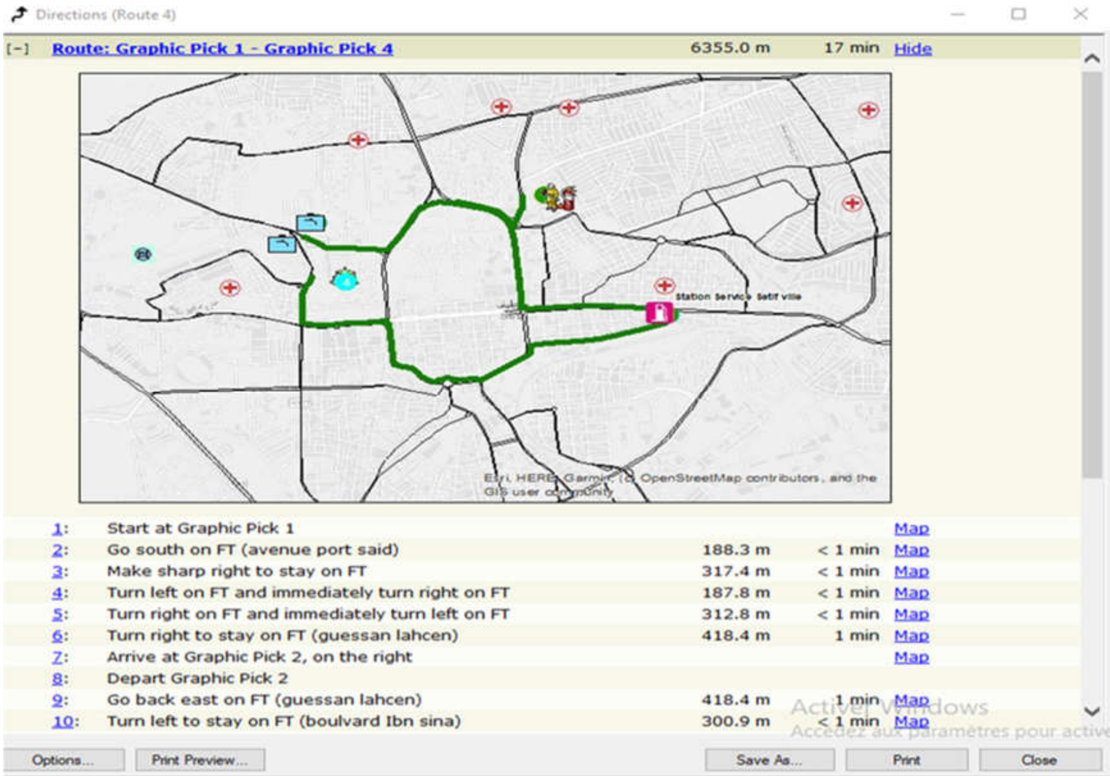

***Figure 3** : Analysis and Modeling of Geometric Networks.*

Source: Author's own creation, using ArcGIS

Intervention Optimization with Network Analyst: The ArcGIS Network Analyst extension was mobilized to simulate the management of emergency interventions. The objective was to determine the optimal paths (the fastest) in a crisis situation, by integrating cost constraints (travel time) and road network restrictions (traffic direction, potential blockades related to the hazard or topography). Two analyses were conducted for emergency planning:

- **Rescue Route:** Optimization of the path between the Civil Protection headquarters (starting point) and the Disaster Zone (target).
- **Evacuation Route:** Optimization of the path between the Disaster Zone (origin of evacuation) and the Main Hospital (destination for victims).

The analysis of the model results provides spatial performance indicators that allow for the assessment of response speed, a determining factor in limiting human and material losses (Tolly et al., 2015), and thus for judging the effectiveness of the Geo-governance in place.

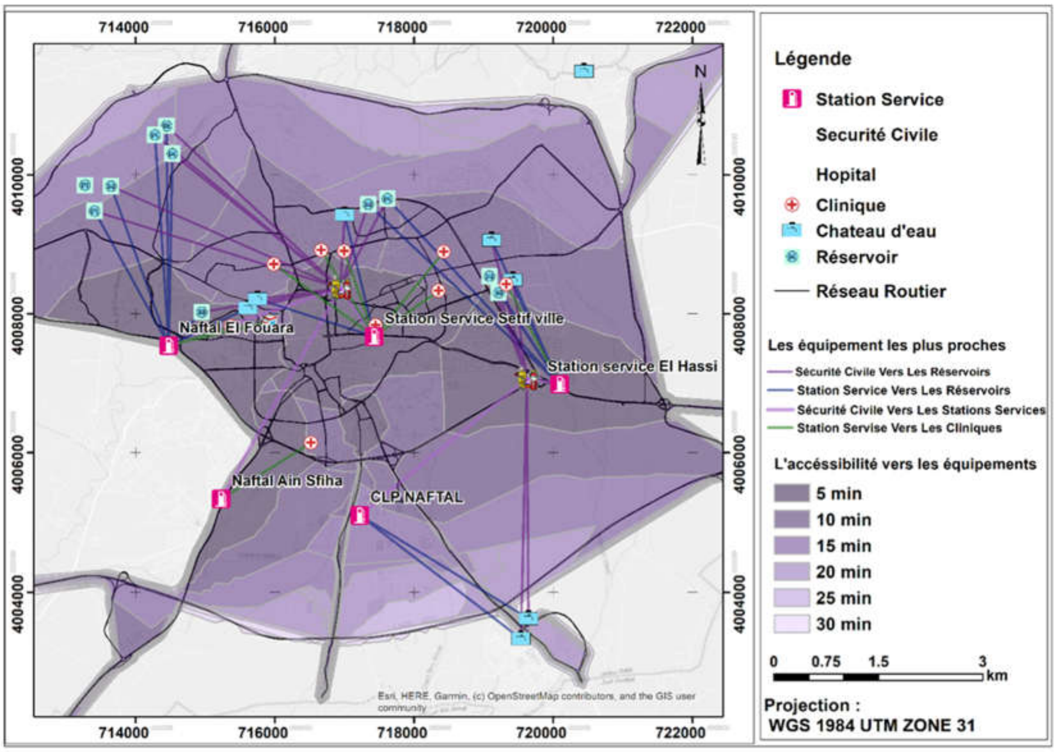

Figure 4 *: Organization of Emergency Response.*

Source: Author's own creation, using ArcGIS

3. Results

3.1. Validation of the Geodatabase and Structuring for Geo-governance

The modeling process resulted in the creation of an operational Geodatabase (GDB), moving beyond simple risk analysis (Melal et al., 2024) to provide a structured decision-making foundation. This GDB integrates the principles of the systemic MADS model (Parent et al., 2006), ensuring the spatial and semantic coherence of the data.

The rigor of converting the Conceptual Data Model (CDM) into the Logical Data Model (LDM) guaranteed the integrity of the database for complex analyses (Caloz, R.). This structured GDB, which explicitly models the Hazard Sources, the Targets (Assets), and the Response Flows, constitutes the digital backbone for Geo-governance in Sétif, facilitating collaboration and transparency among the various crisis management stakeholders (Senior & Copley, 2008).

3.2. Spatial Optimization of Emergency Interventions

The application of the ArcGIS Network Analyst extension (Wang et al, 2007) to Sétif's road network allowed for the quantification of the potential efficiency of the operational response to an industrial accident scenario, based on the shortest travel time.

For the critical route linking the Civil Protection headquarters to the disaster zone, network analysis identified an optimal path. While the empirical route was estimated at 12 minutes for 6.5 km, the optimized route reduced this time to only 8 minutes (5.8 km). This result represents a time saving of 4 minutes, or a 33% reduction in the initial response time. This acceleration is crucial for the effectiveness of rescue operations (Tolly et al., 2015) and directly impacts the capacity to contain the hazard flow (MADS principle) and save lives.

Concurrently, the optimization of evacuation routes toward the main hospital also yielded significant gains. The empirical route was estimated at 25 minutes (10.2 km). Thanks to spatial analysis, the optimal route reduced this time to only 18 minutes (9.5 km). This represents a saving of 7 minutes, or a 28% reduction in the evacuation time. This gain is vital for crisis logistics and victim survival (Chakraborty & Chatterjee, 2011), directly contributing to the improvement of urban resilience.

4. Discussion

The results obtained validate the power of the integrated MADS-GIS approach for risk management. The study provides an operational response to the vulnerability diagnosis (Melal et al., 2024) by delivering the decision support tool capable of minimizing the impact of the modeled consequences.

The quantified reduction in intervention times, ranging from 28% to 33% for critical routes, demonstrates that resilience is a spatially measurable objective in Sétif. This performance confirms the efficiency of Geo-governance when it is equipped with structured spatial information. The GDB, derived from the MADS model, offers a common and georeferenced language to the various intervention bodies, allowing Sétif decision-makers to revise existing ORSEC plans by integrating optimal routes based on evidence-based data, rather than empirical estimations (Senior et al, 2008).

Furthermore, the system allows for the dynamic integration of additional constraints (flooded areas, network outages) in real-time, strengthening the capacity for rapid adaptation, which is essential for sustainable and resilient urban governance.

5. Conclusion

This study addressed the crucial challenge of the operational Geo-governance of industrial risks, using the city of Sétif as a laboratory to analyze the consequences of urban sprawl. In response to the vulnerability established by previous diagnostics (Melal et al., 2024), our work demonstrated the power of the integrated MADS-GIS approach for strengthening urban resilience.

The major contribution of this research lies in the operationalization of systemic hazard analysis (MADS) into a concrete spatial decision support tool. The structuring of the Geodatabase (GDB) via ArcGIS Diagrammer enabled the creation of a reliable information foundation, which is indispensable for multi-stakeholder collaboration and forms the basis of Geo-governance.

The application of the ArcGIS Network Analyst extension validated the effectiveness of this approach by providing quantifiable and decisive results:

- The optimization of rescue routes allowed for a reduction in response time of approximately 33%.

- The optimization of evacuation routes achieved a time saving of up to 28%.

These time savings are a direct and measurable indicator of the improvement in Sétif's operational resilience. They reflect the capacity of the information system to ensure a rapid and coordinated response to hazard flows (Tolly et al., 2015; Senior & Copley, 2008). The model thus provides decision-makers with the factual basis necessary to revise emergency plans and ensure that actions are founded on evidence-based data.

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