Emergency Water Distribution Systems to Improve Spatial Equality and Spatial Equity in a Heterogeneous Community with Differing Mobility Characteristics

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Abstract

Our study addresses challenges in emergency water distribution systems by proposing a hybrid method that optimizes points of distribution (PODs) and mobile delivery systems. The goal is to optimally dispense emergency water to disaster-affected populations while enhancing spatial equality and spatial equity. By considering the physiological and socioeconomic status of the disaster-affected population, our hybrid method addresses the needs of a heterogeneous community. The hybrid method consists of two models: The first model seeks to determine the optimal locations of POD for populations who are deemed physiologically able to visit PODs and pick up their emergency water. In this model, socioeconomic status is incorporated to account for different mobility characteristics of these populations. The second model focuses on determining efficient routes for mobile delivery to populations who are more likely to have physiological limitations that interfere with them traveling to PODs and picking up their emergency water. The proposed method is then validated with an application to the Flint, Michigan, water crisis. Our experiments demonstrate that, compared to the actual setup of PODs, our method shows a 69.30% improvement in objective function value and a 7.05% reduction in the average travel time for people to reach the PODs. Particularly beneficial for those with the longest travel time to the PODs, the model indicates a significant 25.22% decrease in travel time, equivalent to 19.49 minutes. Also, our method suggests the optimal delivery solution involving 20 trucks covering 191.82 kilometers for the target populations. We further conduct a sensitivity analysis to discuss the potential impact of various factors on the operations of the emergency water distribution system. Our results highlight that increasing the number of depots does not necessarily lead to a proportional decrease in vehicle kilometers traveled. We also identify that the most cost-effective vehicle type is a 16-foot truck. These findings provide emergency agencies and policymakers with valuable insights, paving the way for improved guidelines and policies to establish more effective emergency water distribution systems.

Keywords: Water infrastructure; Points of distribution; Mobile delivery; Emergency water distribution; Spatial equality; Spatial equity

1. Introduction

During an emergency response, three types of water distribution systems can be operated by an emergency management agency: points of distribution (PODs), mobile delivery, and direct delivery. PODs are centralized points where supplies are delivered and the public travels to the site to pick up the commodities. Mobile delivery is a method that utilizes vehicles to drive into an affected area and provide commodities at different drop locations or where the need is identified. This type of distribution is common in rural areas and where roads are damaged. Direct delivery is coordinated with a designated location, such as a shelter, feeding site, or hospital, for the delivery of specific items. These items are emergency commodities like food, water, and comfort kits and usually involve quantities that exceed those associated with mobile delivery. One or more of these three distribution systems can be utilized at one time, with multiple distribution systems being used simultaneously to enhance distribution coverage.

Despite the importance of emergency water supply during disasters, few international standards have been developed to guide utilities and authorities in ensuring sufficient water supply and quality. Furthermore, the international standards that do exist have been criticized for being insufficient. For example, Bross et al. (2019), found the International Organization for Standardization (ISO) standards possessed significant gaps that impeded their utility. In the US, the Federal Emergency Management Agency (FEMA) provides guidelines to local emergency management organizations in terms of staffing, site design, equipment, security, and demobilization (FEMA, 2022). These guidelines play a crucial role in shaping the country's emergency responses. The FEMA guidelines tend to focus on PODs and provide detailed instructions related to the design of PODs, and local U.S. agencies have tended to roll out PODs for emergency commodity distribution: 2016 Flint, Michigan, water crisis (PODs for bottled water, water filters, and contamination check kits) (Kim et al., 2021); 2021 Mayfield, Kentucky, tornado (PODs for food, bottled water, baby food, diapers, and cleaning supplies) (Kenny, 2021); 2022 Jackson, Mississippi, water crisis (PODs for bottled water, bulk non-potable water, and hand sanitizer) (MEMA, 2022); and 2023 hurricane through the southeast (PODs for nonperishable food, bottled water, and tarps) (Kaplan, 2023). While POD operations can offer benefits compared to mobile or direct delivery systems, especially in terms of efficiency, scalability, and cost-effectiveness, certain populations would benefit from different emergency distribution systems.

However, the literature and guidelines on emergency distribution systems often fail to consider the specific characteristics (e.g., physiological status, socioeconomic status) of the disaster-affected population (Malak et al., 2020) and how these characteristics could influence the effectiveness of emergency distribution systems. Instead, the emergency literature and guidelines focus mainly on a single type of distribution system, such as POD (Kim et al., 2021), regardless of the impacted population and its characteristics. This reliance on a single emergency distribution system has been recognized as problematic and insufficient to address the needs of diverse target populations (FEMA, 2022). This lack of consideration of the target population's specific characteristics can be highly problematic. For example, consider low-wage workers who have more limited funds and often unreliable transportation options to and from their place of work due to their low private vehicle ownership rates (Kim et al., 2021). These same issues could make it difficult for them to travel to PODs and bring their emergency supplies back to their homes. Therefore, comprehensively addressing the emergency water distribution problem requires considering the characteristics of the affected population.

The goal of our study is to overcome the limitations in the literature and guidelines on emergency water distribution systems by considering spatial equality and spatial equity, especially in a heterogeneous community. Even though Kim et al. (2021) proposed an optimization model for developing POD infrastructure integrating spatial equality and spatial equity into a capacitated facility location model, their study is limited to a singular distribution system and lacks consideration for the heterogeneous community. To overcome these limitations, our study presents a hybrid method that incorporates two optimization models. Model 1 (M1) focuses on the POD system, while Model 2 (M2) considers the mobile delivery system. By incorporating population characteristics (i.e., physiological status and socioeconomic status) into our method, we aim to meet the diverse needs of a heterogeneous community. The key components in our study are presented in Figure 1.

To this end, our study consists of four parts. The first part divides the community into two groups based on their physiological status: Group 1 consists of people who are presumed to be physiologically able to visit PODs and pick up their emergency water; Group 2 consists of people who are more likely to experience physiological limitations that impede them from picking up their emergency water, which implies that regular mobile delivery to their homes is indispensable. The second part analyzes the population's socioeconomic status to estimate individual mobility characteristics. The third part involves developing two optimization models: M1 optimizes POD locations to maximize spatial equity (i.e., minimizing spatial inequity) given a specific level of spatial equality, while M2 optimizes mobile delivery routes for populations with physiological limitations, aiming to minimize the vehicle kilometers traveled (VKT). The final part compares the proposed models' results with the results of mini-max models and the actual setup of PODs during the Flint, Michigan, water crisis.

We begin with the literature review in Section 2 on research related to the Flint, Michigan, water crisis, spatial equality, and spatial equity and then present the background of our method. In Section 3, we introduce the hybrid method to improve emergency water distribution systems in a heterogeneous community. Section 4 presents a case study on the Flint, Michigan, water crisis, in which the data preparation process and the case design for the proposed method are described. We apply the proposed method to the case study and analyze the results in Section 5. Then, we summarize conclusions and discuss recommendations for emergency agencies and policymakers to develop better guidelines and policies for establishing emergency water distribution systems more effectively and more efficiently.

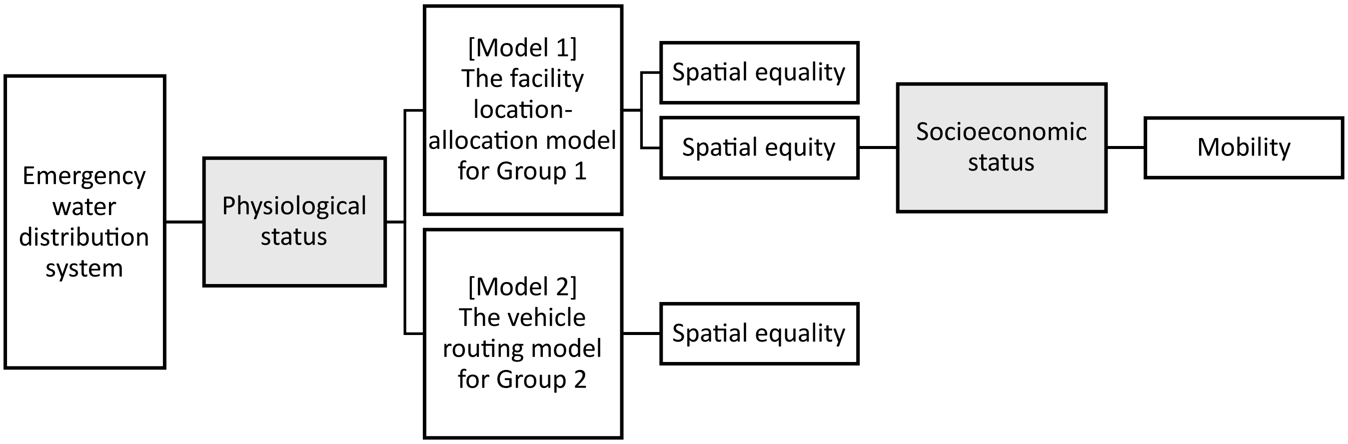


Figure 1. Key components in our study.

2. Literature Review

In this section, we review the research related to the Flint, Michigan, water crisis and categorize it. Then, we review the literature on spatial equality and spatial equity to identify how these perspectives have been considered in contemporary research. We also briefly introduce the background of our method and highlight the main contributions of our study compared to the literature discussed here.

2.1. Overview of Studies Related to the Flint, Michigan, Water Crisis

We conducted a review of studies on topics related to the Flint, Michigan, water crisis to identify researchers' interests and the specific topics they addressed during the crisis. Articles were collected from Web of Science using the following keywords: *Michigan*, *Flint*, *water*, and *crisis* during the period 2015-2021. This keyword search identified 116 articles. Fourteen irrelevant articles were removed. The final 102 articles were categorized as follows: (1) *public, environmental & occupational health*; (2) *environmental and material sciences & water resources*; (3) *government & law, policy, and justice*; (4) *education*; (5) *urban studies, disaster & emergency management*; (6) *social sciences & ethnic studies*; (7) *communication*; and (8) *veterinary sciences* (see Figure 2).

The majority of studies were related to public, environmental & occupational health, followed by an equal number of studies on environmental resources and government policy. The public and environmental health research focused on lead levels in residents' blood (Davis, 2021; Gibson et al., 2020; Gómez et al., 2019; Hanna-

Attisha et al., 2016), Legionnaires' disease (Smith et al., 2019; Zahran et al., 2018), residents' mental health (Cuthbertson et al., 2016; Kruger et al., 2017), and residents' sleep quality (Kruger et al., 2017). Most of the research related to environmental and material sciences & water resources focused on lead contamination in the water supply (e.g., Goovaerts, 2019; Lytle et al., 2019; Olson et al., 2017; Roy et al., 2019), pipe corrosion (Nalley et al., 2019; Pieper et al., 2016), and plastic bottle waste (Wang et al., 2019). The research on government policy focused on regulations related to drinking water quality (Butler et al., 2016; O'Herin, 2018), legal systems (Krsulich, 2017), pipeline replacement policy (Zahran et al., 2020), and socioeconomic disparity and racial inequality in Flint, Michigan (Dorfman and Kenney, 2020; Lee et al., 2016; Schaider et al., 2019; Schnoor, 2016).

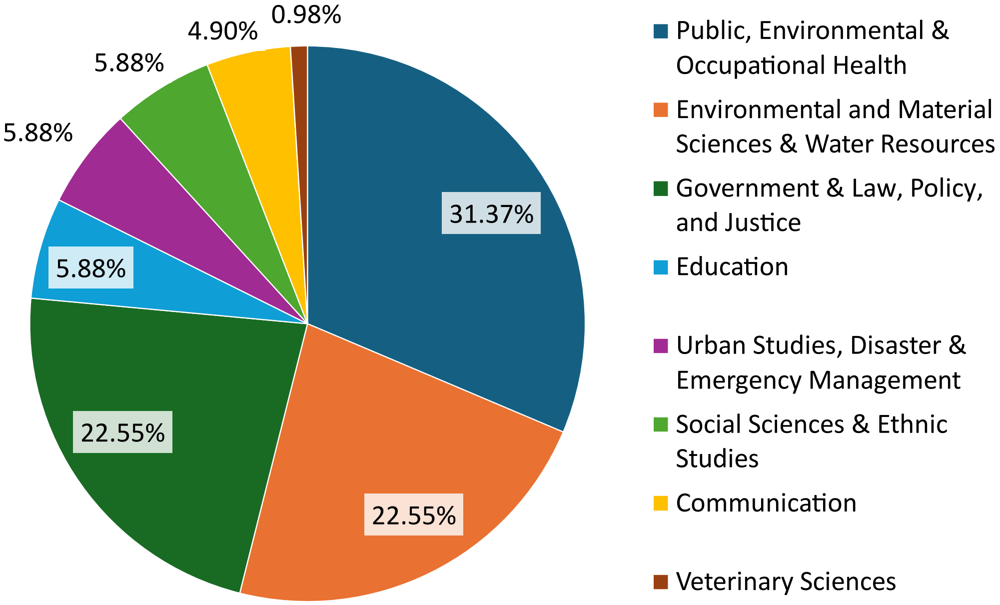


Figure 2. Categorization of the research on the Flint, Michigan, water crisis.

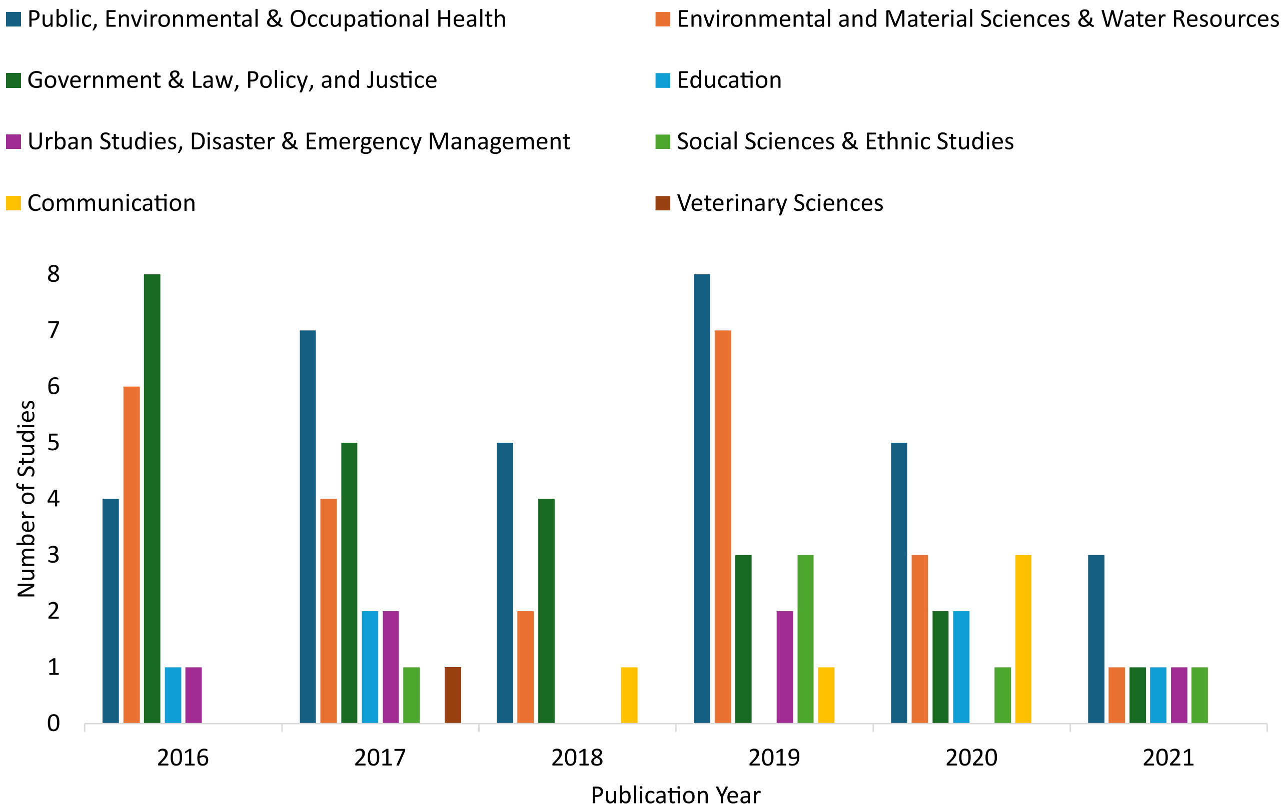


Figure 3. Categorization of the Flint, Michigan, water crisis research by year.

The research conducted by Dorfman and Kenney (2020) and Schnoor (2016), which documented the Flint, Michigan, water crisis, addressed educational aspects within the context of the crisis. Studies in social sciences investigated the Flint water crisis from the perspective of environmental justice (e.g., Benz, 2019; Cassano and Benz, 2019; Henderson and Wells, 2021) and reported concerns from residents (e.g., Heard-Garris et al., 2017; Krings et al., 2019; Sobeck et al., 2020). Multiple communication issues were also studied, such as dissemination of emergency information and social media use (e.g., Day et al., 2019; Jahng and Lee, 2018) and the degree of trust between governments, urban utilities, and the public (e.g., Nowling and Seeger, 2020; Weisner et al., 2020). In the field of veterinary sciences, Langlois et al. (2017) examined 284 dogs in Flint and 47 dogs in East Lancing and compared their overall blood lead concentrations.

A couple of articles addressed emergency management systems, examined the general issues in shrinking communities in the US, and identified current issues in Flint during the water crisis in terms of aging infrastructure and insecure financial standing (Fasenfest, 2019; Morckel, 2017). Miller et al. (2016) emphasized that most disasters involve environmental health components in both direct and indirect ways. Thus, they stressed the importance of considering health components in disaster mitigation planning and operation.

While the research related to the Flint, Michigan, water crisis investigated numerous topics and provided future recommendations for the water supply systems, there remain significant gaps in our understanding of emergency water distribution/supply (e.g., POD, direct/mobile delivery). This underscores the need for additional research on emergency water supply systems. As shown in Figures 2 and 3, the majority of studies were associated with public, environmental & occupational health, environmental and material sciences & water resources, and government & law, policy, and justice. However, the specific emphasis on the topic of emergency water distribution within emergency management was less pronounced. In the literature review, we identified six articles related to emergency management systems in Flint, Michigan. Half of these articles pointed out the lack of emergency management systems in shrinking rural cities and highlighted the importance of cost-effective development tools to support these communities (e.g., Fasenfest, 2019; Miller et al., 2016; Morckel, 2017; Paine and Kushma, 2017) (See Table 1). Sadler (2019) identified that 49% of the Flint, Michigan, population had their municipality misclassified based on their zip code. Since the zip code served as the primary geographic identifier, this misclassification resulted in significant errors involving misrepresenting health statistics. Kim et al. (2021) examined the POD locations in Flint, Michigan, used to distribute water and other emergency supplies and proposed a travel distance-based model to minimize travel distance from users to PODs based on their geographic locations.

Table 1. Emergency management research articles related to the Flint, Michigan, water crisis.

Topic	Year	Method	Highlight	Reference
Health research	2016	Case study	• Identified gap in knowledge about the health impacts of disasters and the benefits of specific interventions. • Most disasters impact environmental health components. • Need a tool to evaluate complex exposures and health effects for vulnerable sub-populations, such as the elderly, children, pregnant woman, and those with socioeconomic and environmental disparities.	Miller et al. (2016)
Role of emergency management	2017	Case study	• Recommend emergency managements inventory drinking water systems through Environmental Protection Agency (EPA)'s a Safe Drinking Water Information Systems and utilize existing documents to identify threats to particular public water systems. • Emergency management needs to adapt the latest techniques to manage community assets.	Paine and Kushma (2017)
Failure of urban planning	2017	Case study	• Identified issues in a shrinking city like Flint in terms of infrastructure, tax revenue, population loss, and public health.	Morckel (2017)
Urban crisis	2019	Case study	• Fiscal crisis faced by shrinking municipalities. • Flint's money-saving plan creates a new long-term debt that would be another fiscal crisis in the coming decades.	Fasenfest (2019)
Misalignment between ZIP codes and municipal boundary	2019	Geospatial analysis	• Quantified the magnitude of potential error inherent in ZIP codes as a unit of analysis. • While ZIP codes can be useful tools for public health planning and policymaking, they can misrepresent health statistics when looking at phenomena that may not coincide well with ZIP code boundaries, including those related to municipal services. • Geographers, epidemiologists, and others with expertise in geographic information systems should be closely consulted on public health research when the location plays an important role in determining outcomes.	Sadler (2019)
Spatial equality and spatial equity in emergency water distribution	2021	Geospatial analysis and optimization	• Found accessibility issues with the PODs during the Flint, Michigan, water crisis. • Identify optimal POD locations that improve travel-distance and travel-time accessibility measurements.	Kim et al. (2021)

2.2. Spatial Equality vs. Spatial Equity

Traditionally, spatial planning and decision-making strategies have been made from the spatial equality perspective (Ventura et al., 2017). This type of spatial planning can be sufficient if every individual has equal mobility and needs a similar level of service regarding the associated problem, such as design of hazardous waste management systems (Rabbani et al., 2018; Yilmaz et al., 2017), emergency response services (Berman et al., 2013; Geroliminis et al., 2011; Kim et al., 2018), shelters and medical supplies (Görmez et al., 2011; Lin et al., 2012; Murali et al., 2012; Woo et al., 2021; Yoon et al., 2022), and refueling/recharging stations (Hwang et al., 2015; Kweon et al., 2017; Ventura et al., 2015).

However, in certain types of problems, it is necessary to take into account varying levels of mobility among individuals and different levels of service. Thus, to attain greater fairness in spatial allocation, spatial equity promotes different availability and different levels of support depending on the socioeconomic status and unique needs of individuals (Espinoza, 2007). Spatial equity has come to the forefront in the search for social justice since it goes beyond the false assumption that everyone's needs are the same and considers the unique needs of socially vulnerable groups. Grier and Grier (1966) were among the first researchers to discuss spatial equity. They reported on the spatial inequity of former federal mortgage policies, which tended to provide easier access to housing opportunities for young, upwardly mobile couples with children than lower income families. The authors claimed that the bias in mortgage policies resulted in lower income families being relegated to public housing. To alleviate the segregation, they suggested the need for comprehensive federal planning and incentives and new types of subsidies to socially vulnerable groups. After Teitz and Bart (1968) outlined a theory of urban public facility location, studies considering equity as well as efficiency in spatial allocation increased dramatically both in number and scope (e.g., Jones and Kirby, 1982; Kirby et al., 1983; Massey and Mullan, 1984; Hay, 1995; Talen and Anselin, 1998). In particular, Massey and Mullan (1984) studied the processes of spatial assimilation from the perspective of socioeconomic status and found that spatial equity failed to be implemented in public facilities serving different socioeconomic groups. Hay (1995) presented eight distinct concepts of fairness and equity as well as justice in geographical research, examined their relevance to the analysis of geographical distributions, and discussed possible combinations of these concepts for geographical operationalization. Talen and Anselin (1998) focused on the relationship between socioeconomic characteristics and accessibility, utilizing geographic methodology and a spatial analytical perspective to evaluate the degree of spatial equity in urban public services.

As society is beginning to recognize the spatial inequity experienced by low-income and other socially vulnerable groups, who usually have lower mobility and lower levels of support, there is an urgent need to consider spatial equity in EM. Lindsey et al. (2001) studied the socioeconomic characteristics of different populations and their access to public green spaces and found that groups with high socioeconomic status had better accessibility to public green spaces than those with low socioeconomic status. Through their ecologic study of environmental equity, Havard et al. (2009) emphasized that socially vulnerable groups, including blue-collar workers, ethnic minorities, and low-income populations, were more likely to be exposed to higher air pollution levels than high-income, White, or highly educated groups. More recently, spatial equity has been analyzed in a variety of spatial problems in terms of sociodemographic and economic characteristics, such as the surface urban heat island problem (Wong et al., 2016), a dockless bike-sharing system (Mooney et al., 2019), and urban transport systems (Park and Chang, 2020).

Spatial equity should play a significant role in how urban planners allocate facility systems, public resources, and different spatial units, with special consideration given to the needs of vulnerable groups to achieve sustainable urban development (Tan and Samsudin, 2017). However, the analysis of spatial equity has raised questions about the appropriate geographical scale of analysis, and measuring spatial equity based on the different abilities and needs of various social groups is quite challenging compared to measuring spatial equality (Truelove, 1993). To address the question of how accessibility to a facility system can be measured from the spatial equity perspective, a number of studies have been published in the second half of the 20th century, including Baxter and Lenzi (1975), Breheny (1978), Hansen (1959), Lee and Lee (1998), Linneker and Spence (1992), and Wachs and Kumagai (1973). The development of information and communications technology and geographic information system (GIS) techniques in the early 21st century opened the doors to more sophisticated ways of measuring spatial equity considering the diverse needs of those from various socioeconomic strata. For instance, Church and

Marston (2003) suggested an accessibility index that reflects the different levels of mobility, distinguishing between individuals with no mobility issues and wheelchair users for facility location planning.

Recent research emphasizes the significance of integrating spatial equity into locational planning, taking into account factors such as socioeconomic status, age, race, and ethnicity. Although both spatial equality and spatial equity are acknowledged as fundamental concepts, their practical implementation in real-world scenarios is impeded by a lack of suitable research methodologies. To address this, it is essential to give due consideration to accessibility indices, particularly in understanding mobility disparities among diverse demographic groups. Examining the accessibility indices, specifically concerning the mobility gap among different groups, allows for a more realistic reflection of challenges such as disparities in access.

2.3. Background on Facility Location-Allocation Model and Vehicle Routing Model

Facility Location-Allocation Model

A facility location-allocation model aims to determine optimal locations for facilities based on specific objectives. The first theoretical study on facility location-allocation was introduced by Weber and Friedrich (1929). Since then, this theory has evolved, incorporating various models and applications, even in post-disaster humanitarian logistics (Ahmadi-Javid et al., 2017). The main objectives in post-disaster humanitarian logistics are to minimize logistic costs and/or reduce human suffering (Holguín-Veras et al., 2013). This field involves the positioning of distribution centers in the most convenient and effective locations to provide emergency relief following a disaster (Hoyos et al., 2015). Finding an effective location-allocation strategy is crucial for disaster response management (Sabbaghtorkan et al., 2020).

Vehicle Routing Model

Once the location-allocation strategy is determined, the associated vehicle routing decisions can be made. A vehicle routing model aims to determine vehicle routes while minimizing total travel cost. The route begins at the depot, traverses the customers in a specified sequence, and returns to the depot (Fisher, 1995). The vehicle routing model was first proposed by Dantzig and Ramser (1959). In the context of disaster response management, this model is frequently used to optimize the routes for delivering emergency supplies to the disaster-affected population (Bruni et al., 2018; Vieira et al., 2021). By introducing the vehicle routing model, optimal routes can be determined, making it possible to deliver emergency supplies efficiently to the disaster-affected population.

Our study identified significant gaps in the literature concerning emergency water distribution systems. Section 2.1 highlights the lack of research on POD planning and operation, while Section 2.2 identifies factors that need to be used for POD installation and points out the lack of suitable methodologies for considering spatial equity in practice. Previous research has primarily focused on single systems like PODs, primarily within the context of spatial equality. However, the concept of spatial equity has not been sufficiently addressed. For instance, considerations of the target population’s physiological and socioeconomic status, which influence their ability to pick up water, have been largely overlooked. To improve both spatial equality and spatial equity in the context of emergency water distribution systems, it is essential to integrate various factors, such as the population’s physiological and socioeconomic status and their preferred areas/locations, into a comprehensive model. Furthermore, there has been limited exploration of the types of public data used and processed to acquire that information.

Our study contributes to the literature in three main ways. First, we introduce a hybrid method that integrates POD installation with mobile delivery systems and apply the models introduced in Section 2.3. By using these models, we can overcome the limitations present in other models that only address single systems. Second, we create detailed travel distance/time datasets. These block-level travel distance/time datasets are based on public datasets. This approach allows for more precise cost/benefit analysis of different water supply strategies and operations, facilitating better planning and decision-making. Third, we consider spatial equality and spatial equity perspectives. Our method aims to enhance both spatial equality and spatial equity by considering multiple factors associated with different populations. The outputs of our study aim to bridge the current gaps in emergency water distribution system research, providing a more comprehensive understanding and approach to planning and operations that consider both spatial equality and spatial equity.

3. Method

Our method aims to improve spatial equality and spatial equity in a heterogeneous community with differing mobility characteristics. To achieve this, we propose two optimization models for distributing emergency water, considering both spatial equality and spatial equity at the same time. We assume the population has different physiological and socioeconomic status. Additionally, we suppose socioeconomic status (i.e., income) affects their mobility (i.e., different transportation options).

M1 is designed to determine the locations of a set of capacitated public facilities. After the locations of the facilities are determined, M2 then determines the optimal routes for delivery from those facilities. Figure 4 shows the proposed methodological flow diagram.

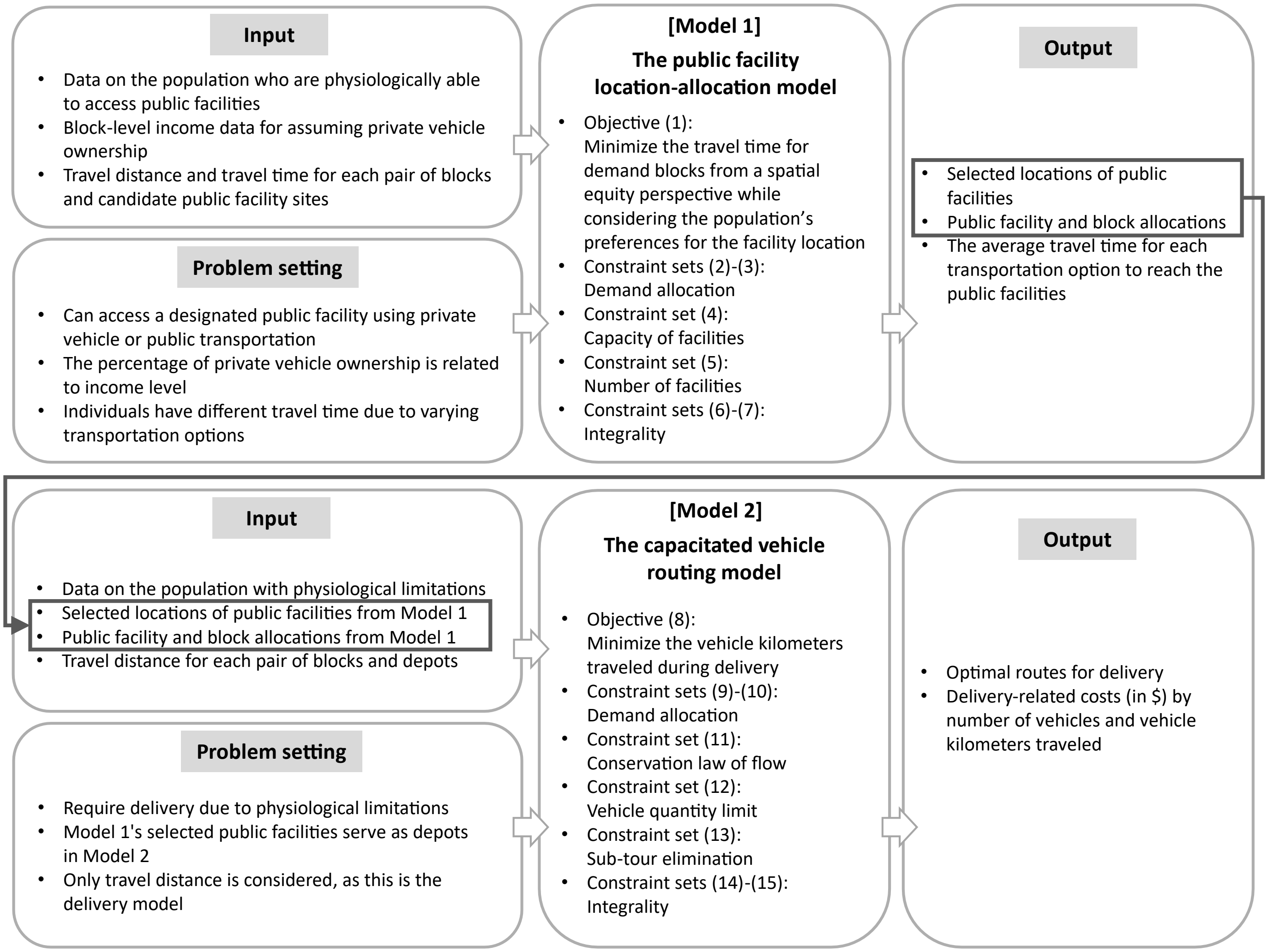


Figure 4. Proposed methodological flow diagram.

3.1. Capacitated Public Facility Location-Allocation Model for PODs

M1 determines the optimal locations of capacitated facilities to minimize the total spatial inequity while meeting the given level of spatial equality. Additionally, our model considers the target population's preferences for facility locations.

3.1.1. Nomenclatures

Sets:

I	Set of demand block groups i
J	Set of candidate sites of public facility j
I_j	Set of demand block groups i whose travel DBA to candidate site j is less than or equal to allowable level of travel DBA r_{ij} for candidate site j; that is, $I_j = \{i \in I \mid a_{ij} \leq r_{ij}\}, \forall j \in J$
J_i	Set of candidate sites j whose travel DBA from demand block group i is less than or equal to allowable level of travel DBA r_{ij} for demand block group i; that is, $J_i = \{j \in J \mid a_{ij} \leq r_{ij}\}, \forall i \in I$
K	Set of transportation options k
G	Set of commercial places g
G_j	Set of commercial places g whose travel DBA to candidate site j is less than or equal to allowable level of travel DBA r_{jg} for candidate site j; that is, $G_j = \{g \in G \mid a_{jg} \leq r_{jg}\}, \forall j \in J$

Parameters:

a_{ij}	Measurable accessibility from demand block group $i \in I$ to candidate site $j \in J$; that is, $a_{ij} = d_{ij}$ if accessibility is in terms of the travel DBA measurement; $a_{ij} = w_{ij}$ if accessibility is in terms of the travel TBA measurement
a_{jg}	Measurable accessibility from candidate site $j \in J$ to commercial place $g \in G$; that is, $a_{jg} = d_{jg}$ if accessibility is in terms of the travel DBA measurement; $a_{jg} = w_{jg}$ if accessibility is in terms of the travel TBA measurement
d_{ij}	Shortest network distance from demand block group i to candidate site j
d_{jg}	Shortest network distance from candidate site j to commercial places g
α_{ijk}	Travel TBA from demand block group $i \in I$ to candidate site $j \in J$ with transportation option $k \in K$
p_i	The population in the demand block group $i \in I$
β_{ik}	Percentage of population p_i using transportation option k, such that $\sum_{k \in K} \beta_{ik} = 100\%, \ \forall i \in I$
w_{ijk}	Travel TBA for the entire population of each demand block group $i \in I$, using their respective transportation option $k \in K$ by each person, to travel to candidate site $j \in J$, that is $w_{ijk} = \alpha_{ijk} p_i \beta_{ik}$
w_{ij}	Total travel TBA in demand block group i to reach candidate site j in terms of spatial equity; that is, $w_{ij} = \sum_{k \in K} w_{ijk}, \forall i \in I, \forall j \in J$
c_j	Capacity of candidate site $j \in J$
m	Number of facilities to be located
r_{ij}	Allowable level of travel DBA from demand block group $i \in I$ to candidate site $j \in J$
r_{jg}	Allowable level of travel DBA from candidate site $j \in J$ to commercial places $g \in G$
w_g	Weight of commercial place, $w_g \in [0,1]$; that is, the minimum level of preference with commercial place $g \in G$ is represented by 0, while maximum level of preference with commercial area $g \in G$ is represented by 1.
$\mathrm{area}(g)$	Area of commercial place $g \in G$
S_j	Customers' preferences for facility $j \in J$, which is presented as the weighted sum function of the areas of all commercial places $g \in G_j$; that is, $S_j = \sum_{g \in G_j} w_g \mathrm{area}(g)$

Decision Variables:

x_{ij}	$= \begin{cases} 1, \text{if demand block group } i \in I \text{ is assigned to a facility at candidate site } j \in J \\ 0, \text{otherwise} \end{cases}$
y_i	$= \begin{cases} 1, \text{if a facility is open at candidate site } j \in J \\ 0, \text{otherwise} \end{cases}$

3.1.2. Travel Distance-Based Accessibility vs. Travel Time-Based Accessibility

To consider spatial equality and spatial equity simultaneously when searching for the potential locations of facilities, we present two different concepts of accessibility.

Travel Distance-Based Accessibility for Spatial Equality

To consider spatial equality, travel distance-based accessibility (DBA) measures accessibility in accordance with only the network distance between demand blocks and capacitated facilities. The travel DBA measurement is based on the spatial equality perspective and assumes that all people have the same level of accessibility without considering how different factors, like socioeconomic status, can result in differences in mobility among demands. For the two sets I and J, referring to the sets of demand blocks and candidate locations of public facilities, respectively, a_{ij} denotes the measurable accessibility between demand block $i \in I$ and facility $j \in J$. If we apply the concept of travel DBA to accessibility, then $a_{ij} = d_{ij}$, where d_{ij} is the shortest network distance between two points: i and j. Then, we can further define the two subsets I_j and J_i for demand block $i \in I$ and facility $j \in J$, respectively, to represent sets of demand blocks i and candidate sites j whose travel DBA is less than or equal to an allowable level of travel DBA, r_{ij}, for candidate facility j and demand block i. By setting this allowable level of travel DBA, spatial equality is considered in our method.

Travel Time-Based Accessibility for Spatial Equity

Compared to the travel DBA, the travel time-based accessibility (TBA) is based on the spatial equity perspective to consider the different levels of accessibility associated with different socioeconomic status of demand blocks. We assume that people with different levels of socioeconomic status have different mobility and transportation options (Iglesias et al., 2019). To measure the travel TBA, α_{ijk} is used as travel TBA from demand block group $i \in I$ to candidate site $j \in J$ with transportation option $k \in K$. Then, we can compute w_{ijk}, which refers to the travel TBA from demand block $i \in I$ to facility $j \in J$ by transportation option $k \in K$, as $w_{ijk} = \alpha_{ijk} d_{ij} p_i \beta_{ik}$, where p_i is the population in demand block group $i \in I$ and β_{ik} the percentage of population p_i using transportation option $k \in K$ such that $\sum_{k \in K} \beta_{ik} = 100\%$ for all $i \in I$. Lastly, we can compute w_{ij}, which refers to the total travel TBA in demand block group $i \in I$, to arrive at candidate site $j \in J$ in terms of spatial equity, as $w_{ij} = \sum_{k \in K} w_{ijk}$. To maximize spatial equity, we minimize the total travel TBA.

3.1.3. Customers' Preferences for Facilities

In addition to accessibility to a facility in terms of travel DBA and travel TBA, customers' preferences for facilities can also be considered when determining potential locations of POD. The customers' preferences for facility $j \in J$, which is denoted by S_j, can be measured in several ways. For instance, (Rosero-Bixby, 2004) suggested estimating S_j by using a vector of characteristics of the candidate site, including size, crowdedness, office hours, and the number of commercial areas within a given range from the public facility j. Considering data availability in our study, for the candidate site of public facility $j \in J$, we present S_j as representing the weighted sum function of the areas of all commercial places $g \in G_j$, which is the set of commercial places whose travel DBA to candidate site j is less than or equal to the allowable level of travel DBA r_{jg} for candidate site j; that is, $S_j = \sum_{g \in G_j} w_g \text{area}(g)$, assuming that the area of each commercial place within a given allowable level of travel DBA r_{jg} from candidate site j affects customers' preferences for facility j. Due to the limited data available, our approach describes S_j in a manner based on the available information.

3.1.4. Binary Linear Programming Model

Considering both travel DBA and travel TBA measurements in terms of both spatial equality and spatial equity as well as customers' preferences for public facilities, a 0-1 linear programming model, denoted by M1, is formulated to determine the potential locations of capacitated public facilities. The number of public facilities to be located, m; their capacity, c_j; and the allowable levels of travel DBA from Group 1 to candidate site and from candidate site to commercial places, r_{ij} and r_{jg}, are given.

$$\text{(M1)} \quad \text{Minimize} \quad \sum_{i \in I} \sum_{j \in J_i} S_j^{-\gamma} w_{ij} x_{ij}, \tag{1}$$

$$\text{subject to} \quad \sum_{j \in J_i} x_{ij} = 1, \forall i \in I; \tag{2}$$

$$x_{ij} \le y_j, \forall\, i \in I, j \in J_i; \tag{3}$$

$$\sum_{i \in I_j} p_i x_{ij} \le c_j y_j, \forall j \in J; \tag{4}$$

$$\sum_{j \in J} y_j = m; \tag{5}$$

$$x_{ij} \in \{0, 1\}, \forall i \in I, j \in J_i; \tag{6}$$

$$y_j \in \{0, 1\}, \forall j \in J. \tag{7}$$

In this formulation, Objective function (1) is to determine the potential locations for m facilities so as to minimize the total travel TBA for demand blocks from the spatial equity perspective while considering the customers' preferences for the facilities at the same time. We note that, in this objective function, the function estimating the customer's preference for the candidate site of public facility j, S_j, is converted to $S_j^{-\gamma}$, where γ refers to the exponent to adjust the impact of S_j on the objective function, since the objective function is minimization. Constraint set (2) ensures that every demand block is assigned to one facility within an allowable level of travel DBA. Constraint set (3) requires that demand blocks are assigned to an open facility. Constraint set (4) is about the capacity of a facility; that is, this constraint set limits the number of residents assigned to each facility so that facilities are not stretched beyond their capacity. Constraint set (5) forces the model to select m facilities. Lastly, all the decision variables are defined as binary by Constraint sets (6) and (7).

3.2. Capacitated Vehicle Routing Model for Mobile Delivery

Once the location-allocation strategy is determined, the associated vehicle routing decisions can be made. M2 determines the delivery routes to minimize the total VKT.

3.2.1. Nomenclatures

Sets:

I	Set of demand block groups i
J	Set of depots j
N	Union of two sets I and J consisting of any points $g, h \in N$; that is, $N = I \cup J$
K	Set of vehicles k for delivery

Parameters:

A	Number of units of need required per capita per weekly unit
p_i	Population in demand block group $i \in I$
q_i	Weekly need for each demand block group $i \in I$; that is, $q_i = p_i \times A$
d_{gh}	Shortest network distance between points g and h, for $g, h \in N$
C_k	Capacity of vehicle $k \in K$

Decision Variables:

x_{ghk}	$= \begin{cases} 1, \text{if point } g \text{ immediately precedes point } h \text{ on vehicle } k \\ 0, \text{otherwise} \end{cases}$
U_{lk}	Auxiliary variable for sub-tour elimination constraints in vehicle k

3.2.2. Mixed-Integer Linear Programming Model

Unlike M1, we do not have to separate travel DBA and travel TBA measurements since the delivery is directly to the demand. Our model optimizes the number of vehicles and delivery routes that minimize the VKT to ensure prompt delivery.

$$\text{(M2)}\quad \text{Minimize} \quad \sum_{g\in N}\sum_{h\in N}\sum_{k\in K} d_{gh}\, x_{ghk}, \tag{8}$$

$$\text{subject to} \quad \sum_{k\in K}\sum_{h\in N} x_{ihk} = 1, \forall i \in I; \tag{9}$$

$$\sum_{i\in I} q_i \sum_{h\in N} x_{ihk} \leq C_k, \forall\, k \in K; \tag{10}$$

$$\sum_{g\in N} x_{hgk} - \sum_{g\in N} x_{ghk} = 0, \forall\, k \in K;\ \forall\, h \in N; \tag{11}$$

$$\sum_{k\in K}\sum_{j\in J}\sum_{i\in I} x_{jik} \leq |K|; \tag{12}$$

$$U_{lk} - U_{ik} + |I| x_{ilk} \leq |I| - 1, \forall l, i \in I;\ \forall\, k \in K; \tag{13}$$

$$x_{ghk} \in \{0, 1\}, \forall g, h \in N; \tag{14}$$

$$U_{lk} \geq 0, \forall l \in I;\ \forall\, k \in K. \tag{15}$$

The Objective function (8) of our formulation focuses on minimizing the VKT during delivery. This optimization aims to ensure efficient delivery to each designated point. Constraint set (9) ensures that every node is entered only once. Constraint set (10) holds the capacity for delivery vehicle $k \in K$. Constraint set (11) is the conservation law of flow; that is, every point entered by the vehicle must be left by the vehicle. Constraint set (12) imposes a limit on the maximum number of vehicles K that can depart from a depot. Constraint set (13) is the Miller-Tucker-Zemlin formulation for the sub-tour elimination that ensures every vehicle on a delivery route is connected to a depot (Miller et al., 1960). Note that $|I|$ refers to the cardinality of set I; that is, $|I|$ denotes the total number of individuals in all demand block groups. Lastly, Constraint set (14) ensures that the decision variable x_{ijk} is binary, and Constraint set (15) forces auxiliary variables U_{lk} to take non-negative values.

4. Case Study: Flint, Michigan, Water Crisis

We validate our method via an application to the Flint, Michigan, water crisis. In Section 4.1, we detail data sources and collection methods in the case study. Section 4.2 outlines the case design and parameter settings.

4.1. Data Preparation

We collected geospatial data to generate a dataset for a case study. The collected data are listed in Table 2.

Table 2. Geospatial data and sources.

#	Data	Source
1	POD locations	City of Flint (2016); Kim et al. (2018)
2	Road network	USGS (2017)
3	Michigan tracts and blocks	U.S. Census Bureau (2018)
4	Pipeline network	James Tchorzynski (2016)
5	Parcels	Melissa Hertlein (2015)
6	Flint water lines with lead violations	City of Flint (2017)
7	City zoning and land use	City of Flint (2018)
8	Schools	Hazard US Multi-Hazard by FEMA

Note: According to the US EPA's Planning for an Emergency Drinking Water Supply, schools are considered as

POD candidate locations (EPA, 2011).

Figure 5 shows 135 block groups, 54 candidate locations for PODs, and the commercial areas as introduced in Section 3.1.3 in Flint, Michigan: Yellow-colored points show block groups, black-colored schools represent candidate POD locations, and grey-colored polygons illustrate commercial areas. Each block contains different populations of Group 1 and Group 2. ArcGIS pro (version 3.2.0) is utilized to graphically present the outputs of our study as well as the geospatial information of PODs and 135 census block points. Figure 6 represents the data preparation process of an origin-destination matrix.

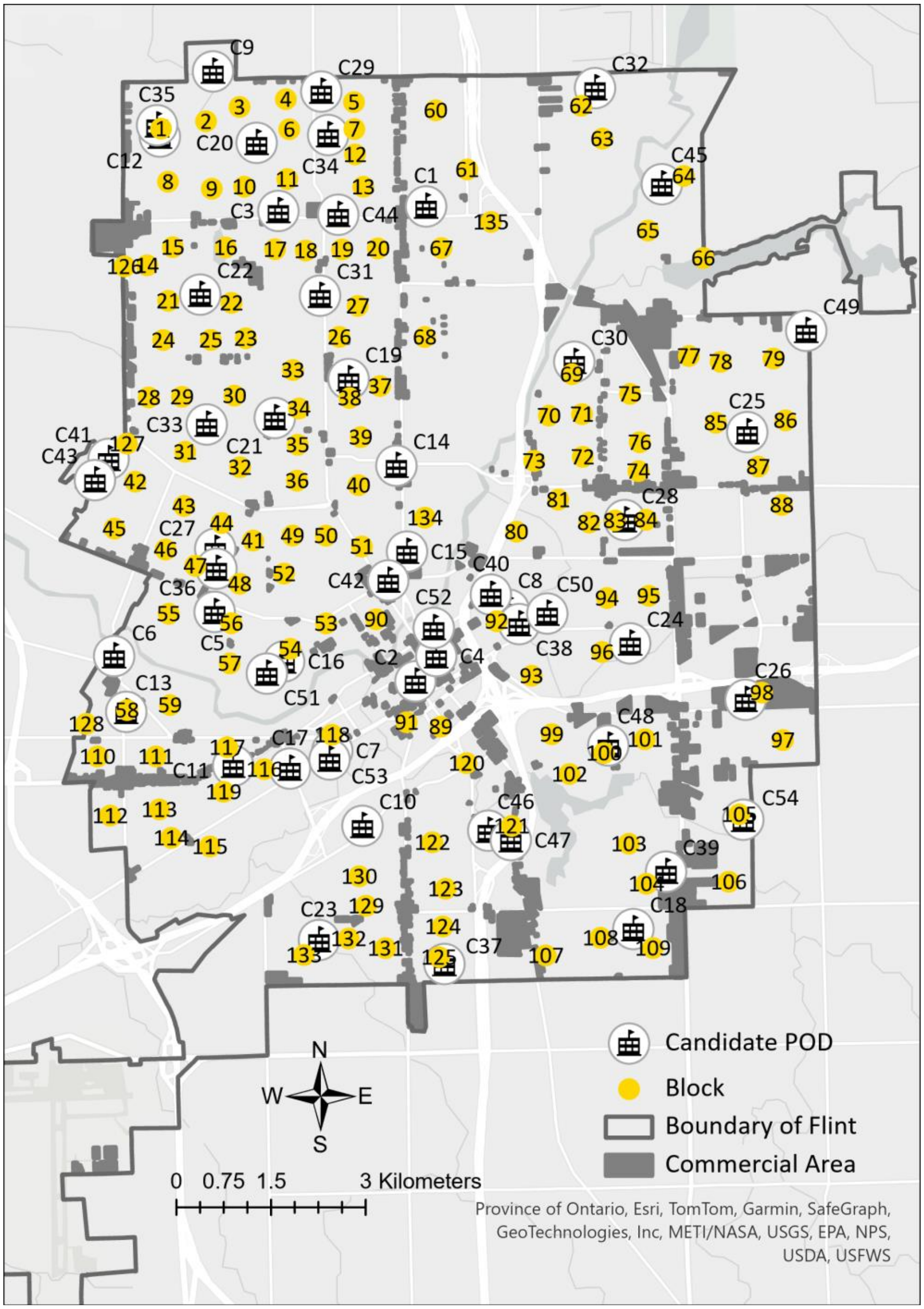


Figure 5. POD candidate locations and commercial zones in Flint, Michigan.
Note: The number in each candidate POD and block represents its respective index.

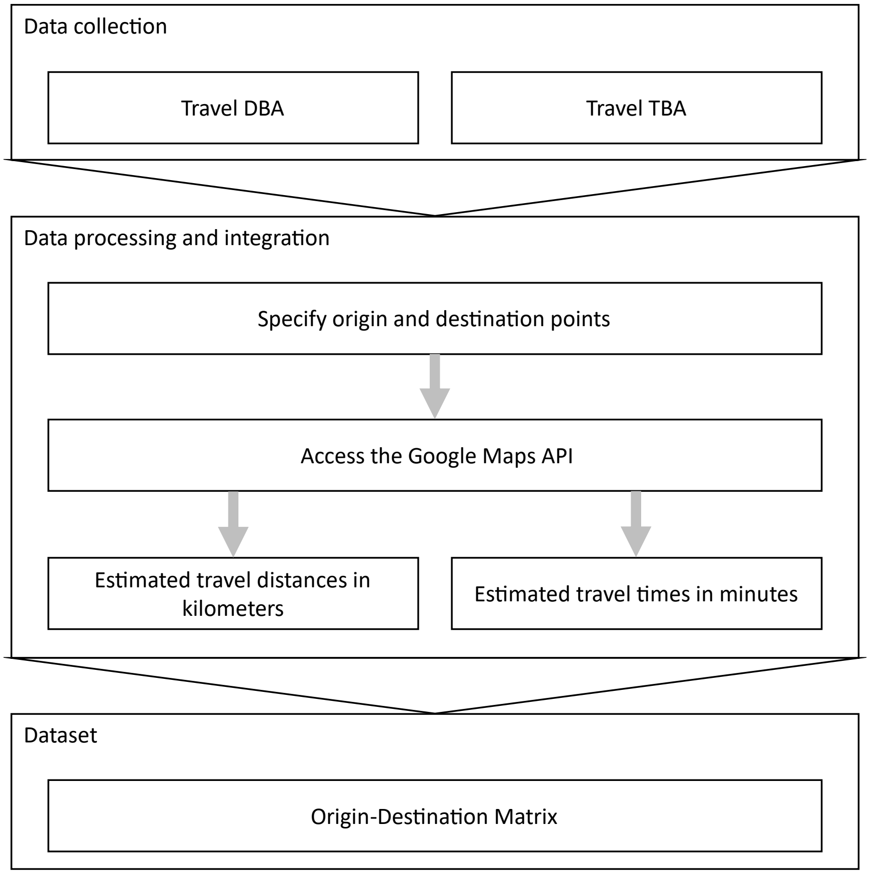


Figure 6. Data preparation process to generate an origin-destination matrix.

4.2. Case Design

In line with FEMA's guidelines, relying on a single distribution system is often inadequate during a disaster. Furthermore, the population aged 65 or older emerges as particularly vulnerable (FEMA, 2021). This demographic has a high prevalence of chronic diseases, with 85% diagnosed with at least one chronic disease (Fong, 2019). As a result, they are likely to face challenges in moving independently and require assistance with emergency water distribution.

To address age-related physiological limitations, we categorize residents into two groups: Group 1 (residents under the age of 65) and Group 2 (residents aged 65 or older). Additionally, we ensure that children are properly taken into account within family units during emergency water distribution. Our model addresses this kind of dependent population by recognizing that they are intrinsically members of their families.

4.2.1. Case Design for M1

In M1, we employ the binary linear programming model to identify the optimal locations for nine POD sites out of the 54 candidate POD sites, aiming to serve the Group 1 population in Flint, Michigan. The objective is to achieve spatial equity and to take into account residents' preferences to ensure overall satisfaction.

For assessing mobility, private vehicle and public transportation are considered as transportation options, denoted respectively as k_1 and k_2. The percentage of private vehicle ownership is estimated based on the socioeconomic status (i.e., income), following Pucher and Renne (2003). Allowable level of travel DBA from demand block group $i \in I$ to candidate site $j \in J$, denoted as r_{ij}, is set to 5 km. The World Health Organization (WHO) recommends that individuals reside within a 5 km radius of a healthcare facility (WHO, 2018). Following this guideline, we determine that the maximum acceptable travel DBA from a demand block to candidate PODs is 5 km. We set the allowable level of travel DBA from a candidate site ($j \in J$) to commercial places ($g \in G$), denoted as r_{jg}, at 0.5 kilometers. A 0.5 km distance aligns with what most people are willing to walk and is considered an acceptable walking distance (Gehl and Svarre, 2013; Sung and Lee, 2015).

Except in Section 5.1.3, which addresses the sensitivity analysis for M1, we consistently maintain the following values: number of PODs at 9, POD capacity at 1,400,000 liters, and per capita daily water supply (PCDWS) at 10 liters. We also note that γ and w_g are set to 1 by default, due to the practical challenges in obtaining precise data, but these values can be updated when real-world data become available.

4.2.2. Case Design for M2

In M2, we optimize mobile delivery routes for the Group 2 population using the mixed-integer linear programming model. Our M2 addresses mobile delivery routes for emergency water distribution to Group 2. The nine PODs selected in M1 serve as depots in our model. We aim to minimize overall travel distance while maintaining vehicle capacity constraints. To solve the model within a reasonable time, we introduce five OR-Tools metaheuristics. With a time constraint of 7,200 seconds, we employ tabu search, simulated annealing, guided local search, greedy descent, and greedy tabu search.

Except in Section 5.2.2, which discusses the sensitivity analysis of M2, we set the homogeneous vehicle as a 16-foot truck, number of PODs at 9, maximum fleet size for each depot at 5, vehicle capacity at 175,000 liters, and PCDWS at 10 liters.

5. Results Analysis

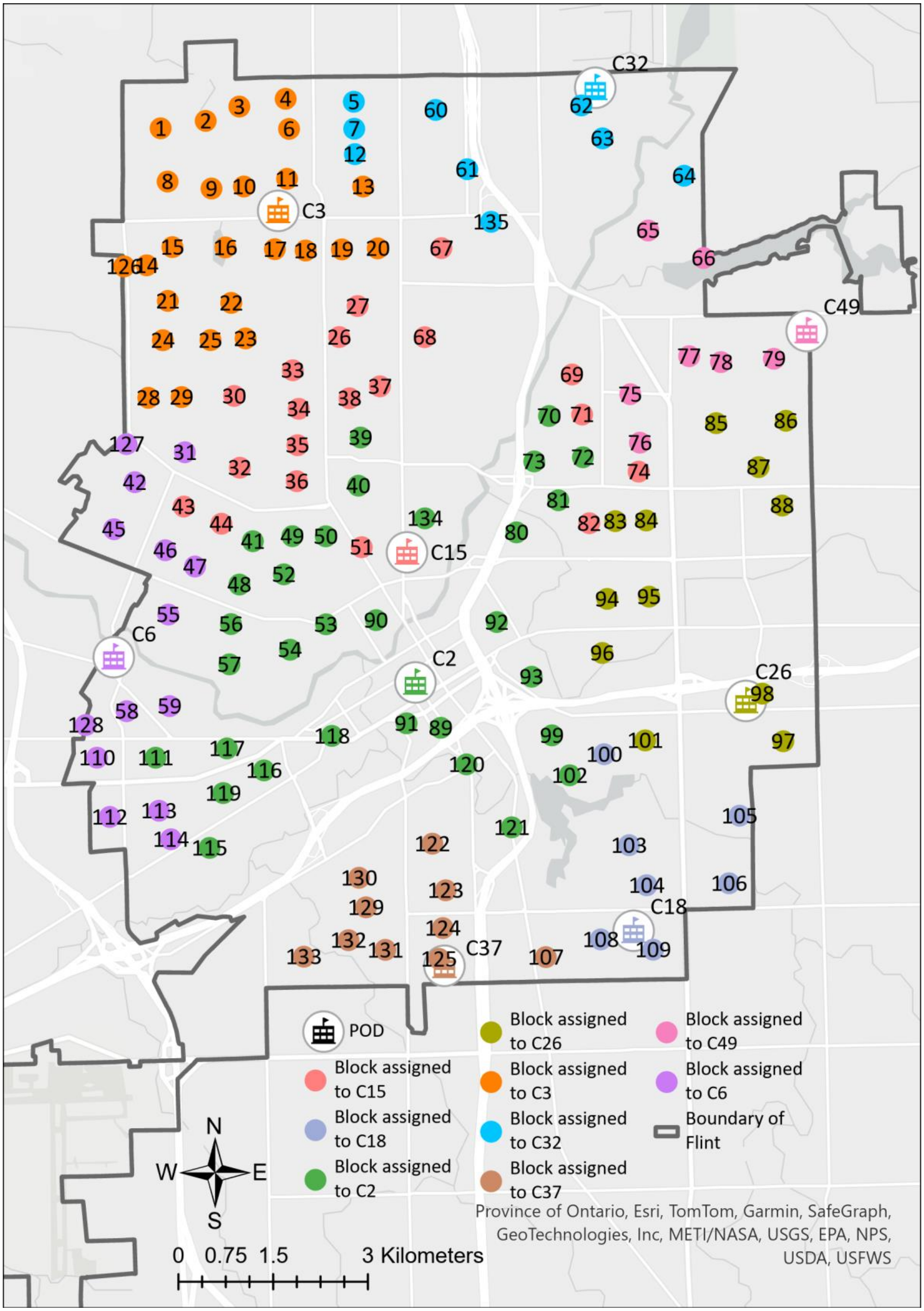
The POD allocation results are described in Section 5.1, and the routing results for mobile delivery are described in Section 5.2. Additionally, a sensitivity analysis is performed to assess which modeling parameters significantly affect each type of scenario. All our numerical experiments are coded in Python version 3.6 and solved by CPLEX version 12.8 (M1) and OR-Tools version 9.6 (M2) through the Python 3 Application Programming Interface on an AMD Ryzen 7 5700X 8-Core Processor CPU with 3.40 GHz and 32 GB RAM desktop PC.

5.1. M1 - POD Locations for Group 1

5.1.1. Optimal POD Locations

Figure 7 provides the selected nine PODs along with their assigned blocks. Detailed information about the assigned blocks and the accessible commercial area of each POD is shown in Table 3.

Our study reveals the optimal locations for nine PODs. Central blocks are intensively connected to PODs indexed as C2 and C15. It is interesting to note that some neighboring blocks of C15 are allocated to C2, despite their close geographical proximity. This allocation pattern to C2 can be attributed to two factors: the size of the commercial area and the condition of public transportation. C2 has a commercial area 3.31 times larger than that of C15, making it a preferable choice. Additionally, C2 benefits from convenient access to public transportation served by three public transportation lines, whereas C15 has only a single public transportation line connected to its site. This characteristic makes C2 a more accessible POD location. To validate this result, we conduct an experiment involving the reallocation of the two closest blocks, Block134 and Block90, to the geographical proximity solution to C15. Surprisingly, this reallocation resulted in a less desirable objective function value: changing from 5.52 to 5.59. Our model considers four factors (i.e., travel TBA, travel DBA, transportation conditions, and commercial areas) to enhance emergency water distribution.



Province of Ontario, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, USDA, USFWS

Figure 7. Optimal POD locations.

Note: The number in each POD and block represents its respective index.

Table 3. Detailed results of the optimal POD locations.

POD	Number of assigned blocks	Number of assigned demands	Total area of accessible commercial spaces (m^2)
C2	32	19,577	286,032.84
C3	25	14,413	50,794.46
C6	14	13,181	41,499.79
C15	19	9,645	86,550.10
C18	7	6,893	273,893.01
C26	12	11,879	633,728.16
C32	9	5,289	34,381.20
C37	10	9,630	230,518.57
C49	7	5,922	65,772.29
Total	135	96,429	1,703,170.42

5.1.2. Comparisons: PODs During the Flint, Michigan, Water Crisis and Proposed PODs

Table 4 compares our proposed nine PODs with the mini-max model and the actual nine PODs opened during the Flint, Michigan, water crisis. In the mini-max model, the objective is to minimize the maximum travel time. The mini-max model can reduce the longest travel time by 27.61 minutes compared to the proposed model.

While it may appear to perfectly guarantee spatial equity, this model overlooks spatial equality. For private vehicle users, the maximum travel time and average travel time are increased by 5.95 and 2.14 minutes, respectively, compared to the proposed model. Consequently, the average travel time for all individuals increases by 1.02 minutes. The mini-max model does not restrict the allowable level of travel DBA. Although this model appears to benefit the most disadvantaged, it violates spatial equality and requires excessive concessions from those who are relatively less disadvantaged.

Our model achieves a remarkable 69.30% reduction in the objective function value and 7.05% reduction in the average travel time compared to the actual PODs opened during the Flint, Michigan, water crisis. Particularly, the maximum travel time for each transportation option, k_1 and k_2, decreases by 70.54% and 25.22%, respectively. Additionally, there is a reduction of 19.49 minutes in the actual travel time for individuals facing the longest travel time (i.e., the worst case), corresponding to the maximum travel time for public transportation users. Notably, the average travel time for all individuals is not significantly different from the average travel time for private vehicles, suggesting a high prevalence of private vehicle ownership in Flint, Michigan. A comparison between actual PODs and proposed PODs reveals our model's outstanding performance.

Table 4. Comparison of mini-max, actual PODs, and proposed PODs.

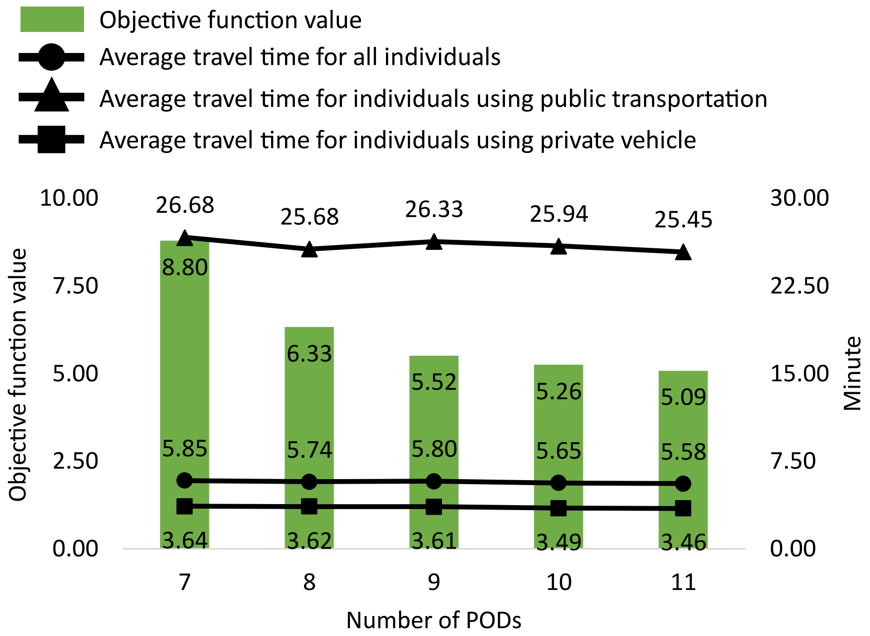
Travel time (min)	Mini-max	Actual PODs	Proposed PODs	Gap (%)
Private vehicle				
Minimum	0.20	0.72	0.20	-72.22
Average	5.75	4.47	3.61	-19.24
Maximum	11.45	18.67	5.50	-70.54
Public transportation				
Minimum	1.08	1.53	1.08	-29.41
Average	21.60	22.90	26.33	14.98
Maximum	30.17	77.27	57.78	-25.22
Average travel time for all individuals (min)	6.82	6.24	5.80	-7.05

Objective function value	-	17.98	5.52	-69.30

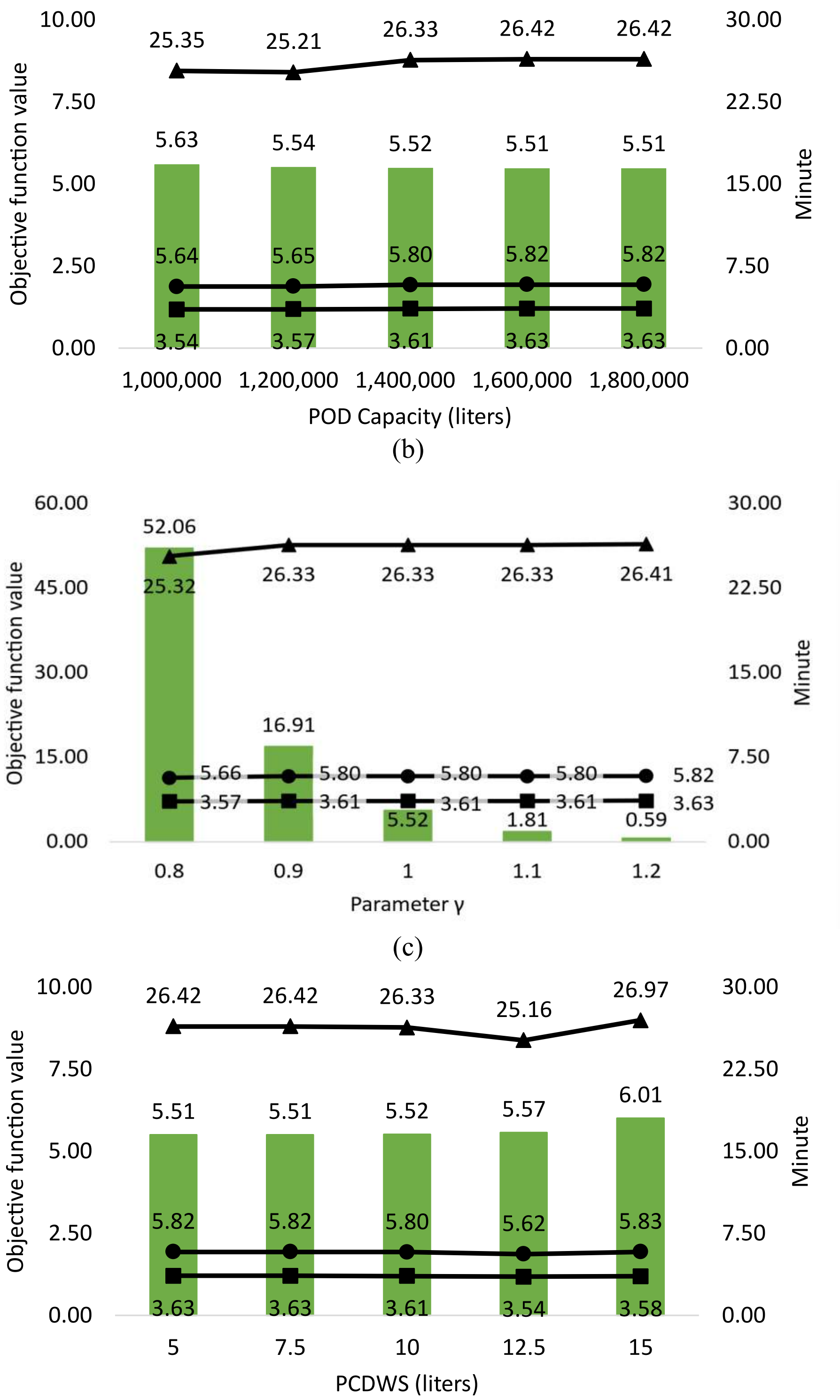
Note: The gap is the relative percentage calculated as $\{(Proposed\ PODs)/(Actual\ PODs) - 1\} \times 100$.

5.1.3. Sensitivity Analysis

Sensitivity analysis is conducted to comprehensively evaluate the impact of parameters on both our introduced optimization model and the optimal locations for the PODs. These analyses encompass a broad range of parameter variations, ensuring a thorough assessment of their effects. Specifically, sensitivity analyses of four parameters are conducted: (a) number of PODs m, which is the count of opened PODs; (b) POD capacity C_j, defined as maximal coverage that each POD can offer; (c) γ, introducing an exponent to modulate the influence of residents' preferences for the facility (POD) on the objective function; and (d) PCDWS, referring to the daily water supply per individual. In consideration of the PCDWS, we set 10 liters per person a day. When a resident collects their water supply, they receive an amount that is intended to last them for seven days. However, the various emergency water supply standards offer differing recommendations. For example, FEMA (2004) recommends 1 gallon (approximately 3.8 liters) of water per person daily, while Reed and Shaw (1994) suggest 3 to 5 liters as a survival minimum and 15 to 20 liters as an optimal amount per day. To address this, we conduct a sensitivity analysis for the PCDWS parameter.



(a)



(b)

(c)

(d)

Figure 8. Results of the sensitivity analysis for different parameters: (a) number of PODs, (b) POD capacity, (c) parameter γ, and (d) PCDWS.

5.1.3.1. Number of PODs (m)

As shown in Figure 8(a), increasing the number of PODs has a positive impact on the objective function value.

This is because it expands the choices available to the Group 1 population. This increase in options raises the likelihood of residents being assigned to a POD that is close to them, consequently reducing the objective function value. Moreover, a continuous decrease in the average travel time for private vehicles is observed as the number of PODs increases. However, the situation is different when it comes to public transportation users. When there are nine PODs, there is an increase in the average travel time for public transportation users as well as the private vehicle users, compared to eight PODs. Despite the increase in travel time, the objective function value improves compared to eight PODs. This improvement can be attributed to POD preference, highlighting the trade-off between factors.

When comparing scenarios with eight or ten PODs, it is observed that in the scenario with ten PODs, the average travel time for public transportation users increases. Specifically, there is an increase of 0.26 minutes in average travel time for these users when the number of PODs is increased from eight to ten. However, the average travel time for all individuals is slightly lower with ten PODs (reduced by 0.09 minutes) because the average travel time for private vehicle users is 0.13 minutes shorter. This difference in average travel time between all individuals and public transportation users reflects the prevalence of private vehicle ownership in Flint, Michigan. This underscores the importance of taking into account the population's mobility when making decisions related to POD locations.

5.1.3.2. POD Capacity

Increased POD capacity has a positive impact on reducing the objective function value and increases the likelihood of each POD being chosen by a larger number of individuals, as illustrated in Figure 8(c). However, it is crucial to note that there is a trade-off involved; as capacity increases, the average travel time for all individuals tends to rise due to the individuals' preferences for specific PODs. However, it is interesting to note that when $c_j = 1{,}200{,}000$, the average travel time for public transportation users decreases from when $c_j = 1{,}000{,}000$. At $c_j = 1{,}400{,}000$, we observe a sudden increase in travel time for public transportation users compared with $c_j = 1{,}200{,}000$. This increase occurs due to the delicate balance between two key parameters of the objective function: travel time and preference for particular PODs. Furthermore, once the capacity reaches $c_j = 1{,}600{,}000$, additional increases do not reduce travel time or improve the objective function value. This suggests that beyond this threshold, additional expansions may not bring significant benefits in terms of travel time reduction or POD preference for Group 1.

5.1.3.3. Parameter γ

According to Figure 8(c), examination of parameter γ reveals its direct impact on our objective function. Initially, we set γ to a default value of 1. Notably, the objective function value can range from 52.06 to 0.59 within the γ value range of 0.8 to 1.2. This is intuitive, as γ directly affects the objective function and thus impacts the results. even minor adjustments in the parameter γ can have a significant impact on the objective function value. Within the γ range of 0.9 to 1.1, we observe identical average travel time for the same POD-block pair matching. However, the objective function value varies significantly across different scenarios, underlining the substantial impact of the γ parameter. This emphasizes that even slight changes in γ, typically around 0.1, can result in substantial alterations in the objective function value. Additionally, results within the γ range of 0.9 to 1.1 exhibit no impact on the allocation results. This shows that γ within this range affects only the calculation of the objective function value without altering the results. However, when γ exceeds 1.2, we observe an increase in travel time for all individuals. This indicates an amplified influence on POD preference, leading to the allocation of more users to PODs that provide higher preference. Additionally, an increase in the value of γ can lead to an increase in the average travel time for both private and public transportation users. Managing parameters related to S_j is crucial for achieving meaningful results in our overall study.

5.1.3.4. PCDWS

As shown in Figure 8(d), the increase in PCDWS also increases the objective function value. This is because when PCDWS increases, the number of people that PODs can serve decreases. Overall, the results indicate that changes in PCDWS have minimal effects on average travel time parameters. The comparison between the 5 liter and 7.5 liter scenarios reveals no statistical difference. However, there are slight fluctuations in these parameters as water supply levels increase.

5.2. M2 – Mobile Delivery Model for Group 2

5.2.1. Selected Routes for Mobile Delivery

Five metaheuristic methods effectively address the optimal routes for mobile delivery across 135 census block groups (refer to Table 5 and Figure 9). The tabu search identifies the nearest optimal solutions out of five methods, covering the VKT of 191.82 km with 20 trucks. This surpasses the second-best guided local search by a reduction of 0.23 km, proving the superiority of this approach.

The results of all five metaheuristic methods, particularly in terms of the POD indexed as C3, are presented in Table 6 and Figure 10. Except for the guided local search, the methods utilize three trucks in this POD. The guided local search utilizes one additional truck, minimizing the total travel distance compared to the simulated annealing, greedy descent, and greedy tabu search. Figure 10 illustrates that the routing of each method deviates from the tabu search method at this POD. The variations in outcomes result from differences in the selected visiting points, emphasizing distinct characteristics for each method. The tabu search method yields the shortest VKT, with a minimum reduction of 0.23 km (compared to the guided local search) and a maximum reduction of 4.35 km (compared to the simulated annealing, greedy descent, and greedy tabu search) in C3. Furthermore, the cost gap compared to other methods in this POD ranges from a minimum of $0.87 to a maximum of $174.05. Additional details on cost are listed in Table 7.

The tabu search shows the maximum distance from the PODs indexed as C2 and the minimum distance from the PODs indexed as C49. For the PODs indexed as C6, C18, C26, C32, and C49, all five methods select the same routes. This suggests a high likelihood of converging toward a near-optimal solution. Furthermore, we observe that the greedy descent and greedy tabu search generate the same routes, resulting in the worst VKT outcomes. This highlights the fact that the greedy strategy heavily relies on local information and has limited randomness in route selection.

While the route for the C49 appears curved in Figure 9, it is the optimal choice based on actual road data usage. For example, if the truck visits the 5th visiting block before the 4th visiting block, the VKT will increase by 0.69 km. The five metaheuristic methods provide insights into the performance and applicability of solution approaches for optimizing mobile delivery operations.

Table 5. Results of five metaheuristic methods.

POD	Number of demand block (number of demand)	Tabu search			Guided local search			Simulated annealing			Greedy descent and Greedy tabu search		
		Number of trucks	VKT (km)	Cost ($)	Number of trucks	VKT (km)	Cost ($)	Number of trucks	VKT (km)	Cost ($)	Number of trucks	VKT (km)	Cost ($)
C2	32 (998)	4	43.91	704.78	4	43.91	704.78	4	45.22	705.04	4	45.22	705.04
C3	25 (956)	3	25.09	527.02	4	25.32	701.06	3	29.44	527.89	3	29.44	527.89
C6	14 (562)	2	20.21	352.04	2	20.21	352.04	2	20.21	352.04	2	20.21	352.04
C15	19 (567)	2	26.40	353.28	2	26.40	353.28	2	26.48	353.30	2	26.48	353.30
C18	7 (379)	2	13.54	350.71	2	13.54	350.71	2	13.54	350.71	2	13.54	350.71
C26	12 (715)	3	22.38	526.48	3	22.38	526.48	3	22.38	526.48	3	22.38	526.48
C32	9 (195)	1	16.57	177.31	1	16.57	177.31	1	16.57	177.31	1	16.57	177.31
C37	10 (494)	2	12.64	350.53	2	12.64	350.53	2	12.64	350.53	2	12.72	350.54
C49	7 (233)	1	11.09	176.22	1	11.09	176.22	1	11.09	176.22	1	11.09	176.22
Total	135 (5,099)	20	191.82	3,518.36	21	192.05	3,692.41	20	197.56	3,519.51	20	197.63	3,519.53

Note: The rental cost of a 16-foot truck is $174.00 per day, inclusive of unlimited mileage and taxes, and the fuel cost for a 16-foot truck is $0.20 per kilometer (As of August 15, 2023. Sources: https://www.pensketruckrental.com/trucks-and-vans/cargo-van/; https://gasprices.aaa.com/).

Table 6. Results of five metaheuristic methods for the POD indexed as C3.

Truck number		Tabu search	Simulated annealing, greedy descent, and greedy tabu search	Guided local search
1	VKT	5.52	10.16	8.29
	Load	321	317	304
	Route [a]	POD → 11 → 1 → 8 → 10 → POD	POD → 21 → 24 → 29 → 28 → 126 → 1 → POD	POD → 18 → 19 → 20 → 13 → 11 → 6 → 4 → 3 → 10 → POD
2	VKT	9.91	8.78	5.81
	Load	313	317	310
	Route	POD → 18 → 17→ 22 → 23 → 25 → 29 → 28 → 24 → 21 → 126 → 14 → 15 → POD	POD → 6 → 4 → 3→ 2 → 8→ 14 → 15 → POD	POD → 8 → 1 → 2 → 9 → POD
3	VKT	9.67	10.50	9.49
	Load	322	322	303
	Route	POD → 19 → 20 → 13 → 6 → 4 → 3 → 2 → 9 → 16 → POD	POD → 18 → 19 → 20 → 13 → 11 → 10→ 9 → 16 → 23 → 25 → 22 → 17→ POD	POD → 17 → 22 → 23 → 25 → 29 → 28 → 24 → 21 → 126 → 14 → 15 → POD
4	VKT			1.73
	Load			39
	Route			POD → 16 → POD
	Total VKT	25.09	29.44	25.32

Note: The routes of each metaheuristic method are visualized in Figure 10.

Table 7. Vehicle cost of each vehicle type.

Vehicle type	Fuel type	Fuel cost per liter ($)	Fuel efficiency (km/L)	Fuel cost per km ($)	Daily rental cost ($)
Cargo van	Gasoline	1.02	5.10	0.20	165.00
12-foot truck	Gasoline	1.02	5.10	0.20	165.00
16-foot truck	Gasoline	1.02	5.10	0.20	174.00
22-foot truck	Diesel	1.14	5.52	0.21	1,014.00
26-foot truck	Diesel	1.14	5.52	0.21	1,014.00

Note: The costs are based on information available as of August 15, 2023 (Sources: https://www.pensketruckrental.com/trucks-and-vans/cargo-van/; https://gasprices.aaa.com/).

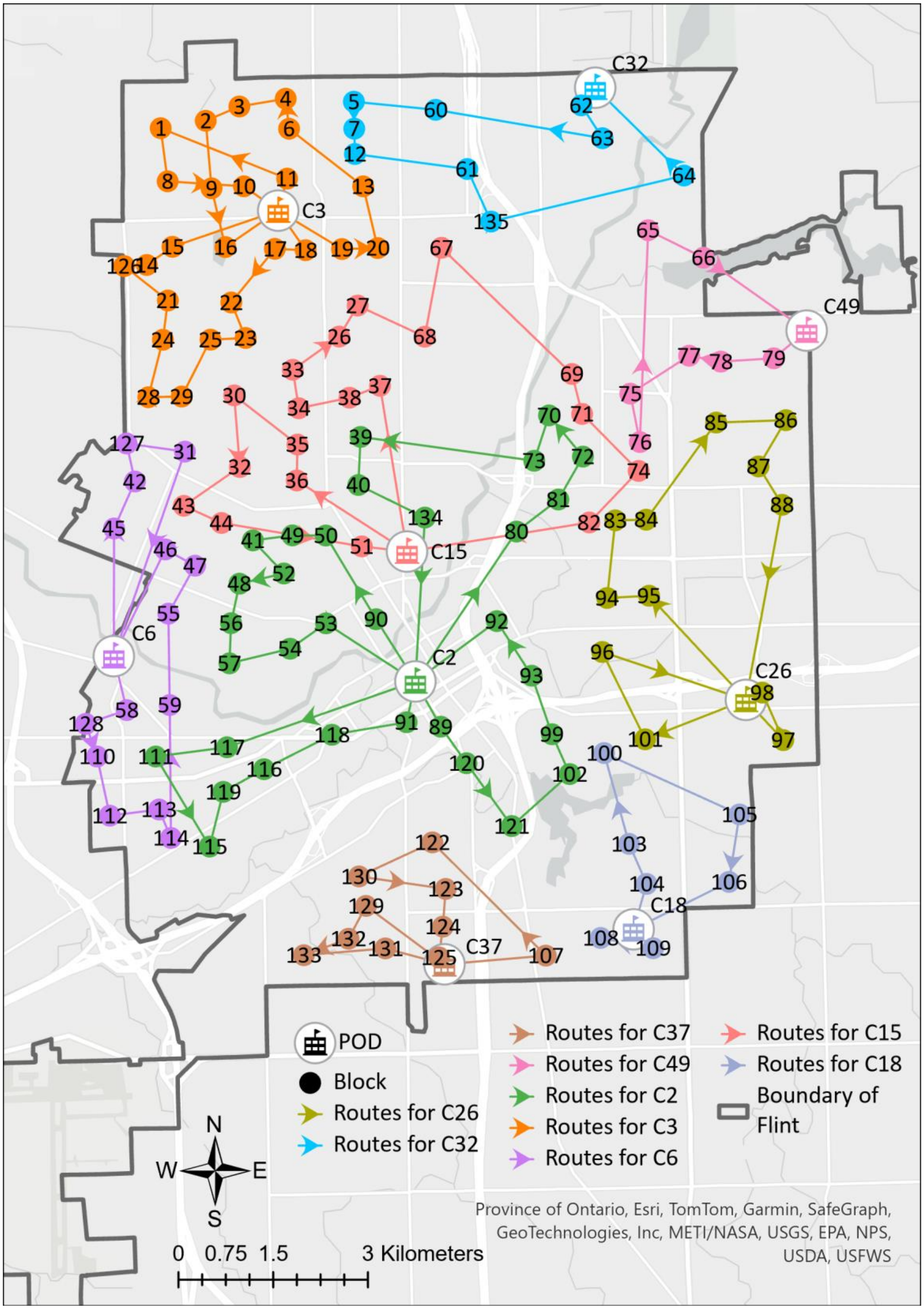
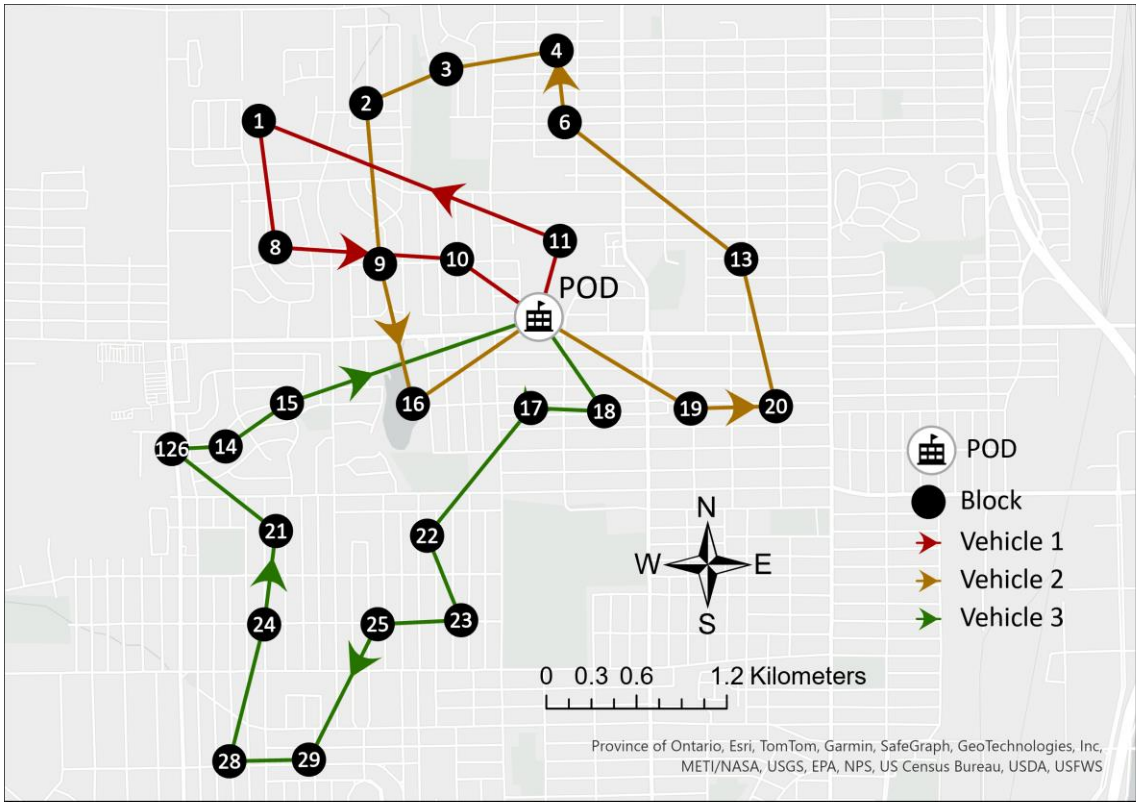
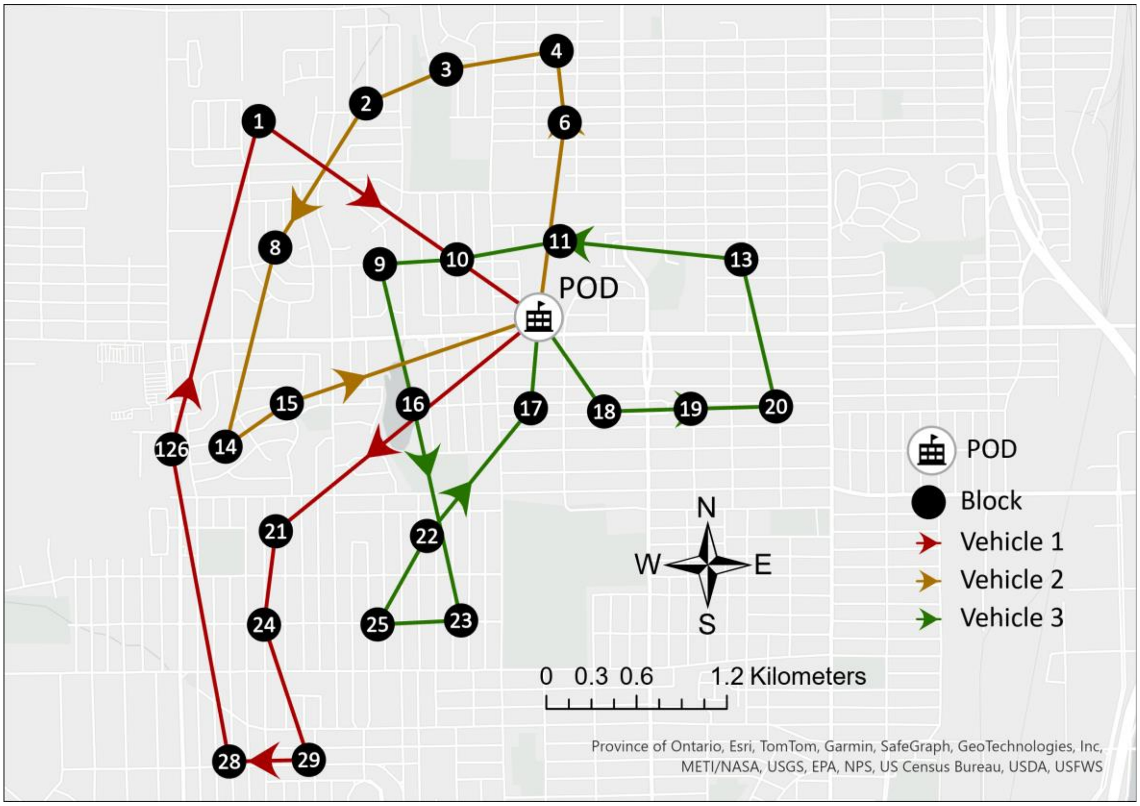


Figure 9. Selected routes for mobile delivery.



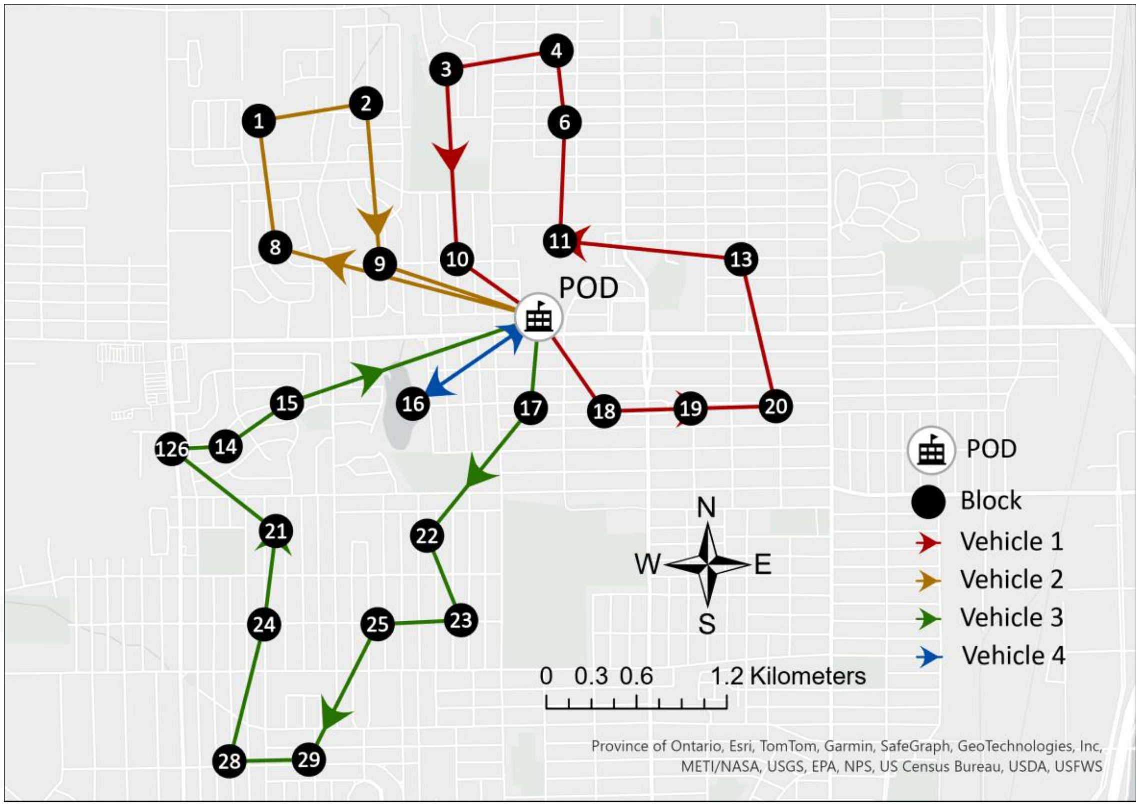
Province of Ontario, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA, USFWS

(a)



Province of Ontario, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA, USFWS

(b)



(c)

Figure 10. Visualization of the results from 5 metaheuristic methods for the POD indexed as C3: (a) tabu search; (b) simulated annealing, greedy descent, and greedy tabu search; (c) guided local search.

We conduct an additional experiment for the mini-max model using the tabu search to compare its performance with that of our proposed model. The main comparison is summarized in Table 8. Since the mini-max model aims to minimize the maximum travel distance between demands and the depot, it yields shorter maximum distances at every node than our proposed model. However, the total VKT by the mini-max model (i.e., 285.95 km) is 94.13 km longer than that of our proposed model (i.e., 191.82 km). Additionally, the mini-max model requires 21 more trucks than our model, resulting in a total cost that is $3,672.83 more. The comparison shows that while the mini-max model reduces the maximum distance between demand and depot, it results in an increase in both VKT and costs. Since the cost is represented as the expense of a single event, it will increase astronomically in long-term operations. Therefore, the proposed model is likely better suited for both VKT and cost savings compared to the mini-max model.

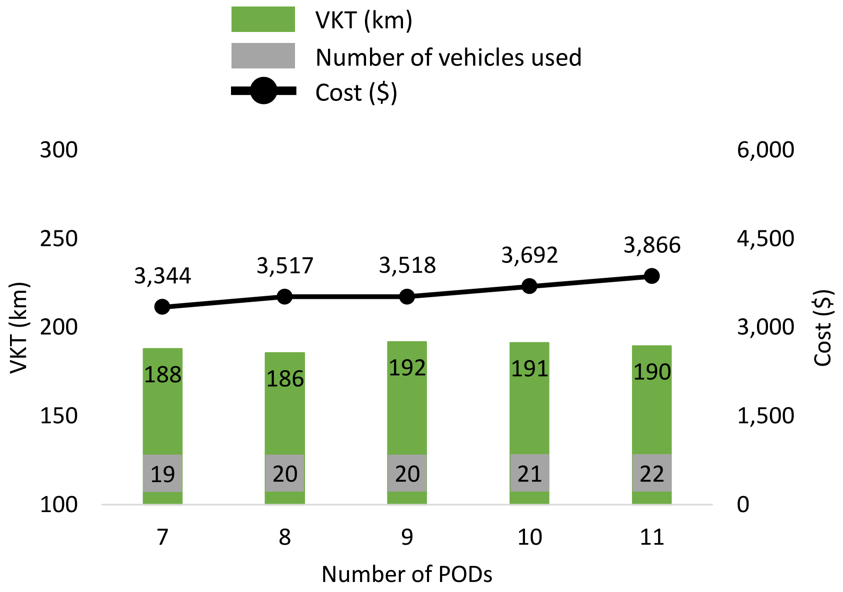
Table 8. Results for mini-max model and the proposed model.

Depot	Mini-max model				Proposed model			
	Number of trucks	VKT (km)	Maximum distance (km)	Cost ($)	Number of trucks	VKT (km)	Maximum distance (km)	Cost ($)
C2	5	50.09	9.15	880.02	4	43.91	10.22	704.78
C3	5	31.51	5.57	876.30	3	25.09	8.90	527.02
C6	5	31.57	4.57	876.31	2	20.21	10.91	352.04
C15	5	43.34	8.60	878.67	2	26.40	14.33	353.28
C18	3	15.83	4.25	525.17	2	13.54	10.00	350.71
C26	5	39.67	5.63	877.93	3	22.38	9.78	526.48
C32	4	29.09	6.76	701.82	1	16.57	13.21	177.31

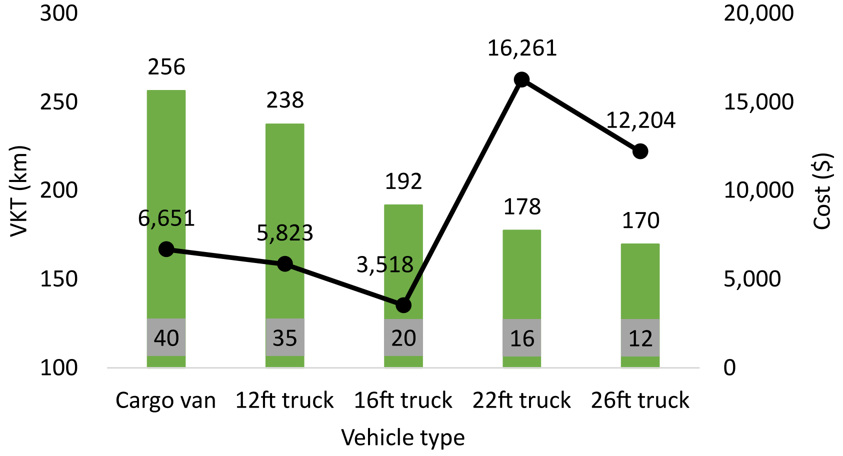
C37	5	19.53	4.23	873.91	2	12.64	7.66	350.53
C49	4	25.33	5.89	701.07	1	11.09	8.15	176.22
Total	41	285.95	-	7,191.19	20	191.82	-	3,518.36

5.2.2. Sensitivity Analysis

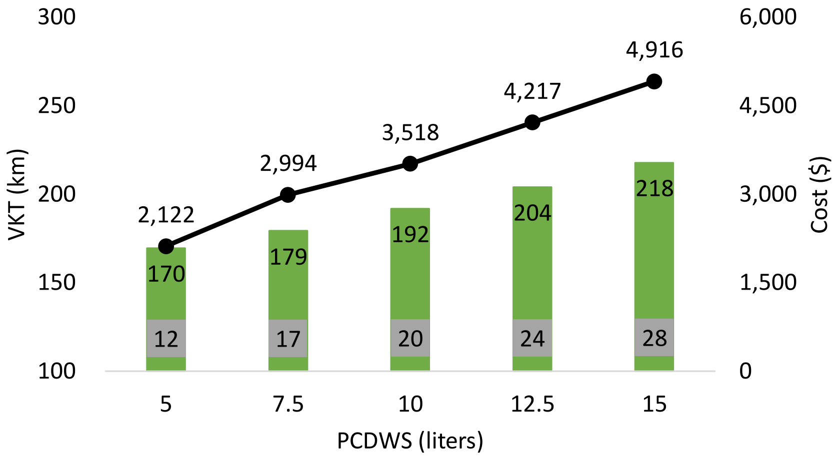
Similar to the sensitivity analysis conducted for M1 in Section 5.1.3, in this section, we perform the sensitivity analysis for M2. As with the earlier sensitivity analysis, we intend to analyze the variations in (a) the number of PODs, m, which serve as depots; (b) the vehicle type, C_k, related to how much water a vehicle can carry; and (c) PCDWS, the daily supply amounts. The examination of these three parameters contributes to a more intuitive understanding of distributing emergency water through mobile delivery for Group 2.



(a)



(b)



(c)

Figure 11. Results of the sensitivity analysis for different parameters: (a) number of PODs, (b) vehicle type, and (c) PCDWS.

5.2.2.1. Number of PODs

As shown in Figure 11(a), it is evident that the variations in the number of PODs lead to nonlinear outcomes. Surprisingly, with eight PODs, the shortest VKT is achieved, while with nine PODs, the longest VKT is observed. This underscores that the number of PODs does not significantly influence the VKT. For instance, VKT with seven PODs is shorter than with eleven PODs, indicating that having more PODs does not significantly contribute to minimizing VKT. From a cost perspective, having seven PODs proves to be the most economical choice. This highlights that the operating cost is more influenced by the number of trucks used than by the VKT.

5.2.2.2. Vehicle Type

As shown in Figure 11(b), VKT varies significantly based on the vehicle type. The capacity of a vehicle differs based on its type, allowing larger vehicles to deliver more emergency water. As the capacity increases, both VKT and the number of vehicles used decrease because the vehicle can carry more emergency water on each trip. Expenses incurred by each vehicle type are influenced by various factors, fuel efficiency and daily rental costs, as evidenced in Table 7. The most significant difference in rental costs is observed when transitioning from a 12-foot truck to a 22-foot truck. This indicates that, even with a reduced number of vehicles used, the type of vehicles significantly impacts expenses. Our analysis highlights that the 16-foot truck, which is used in our M2, is cost-efficient. We can reduce the cost by using 16-foot trucks ranging from a maximum of $12,742.92 to a minimum of $2,304.15 in 2023 dollars.

5.2.2.3. PCDWS

As shown in Figure 11(c), the analysis reveals a clear characteristic of PCDWS. As PCDWS increases, a single truck cannot handle the load due to its capacity constraints. Consequently, three associated factors also increase: VKT, the number of trucks used, and operating costs. This analysis reveals a consistent pattern that aligns with the results based on vehicle type, which is closely related to vehicle capacity. As the amount of water provided increases, more deliveries are required, resulting in differences in operations and costs.

6. Discussion

Our study explores an emergency water distribution system with the aim of enhancing both spatial equality and spatial equity for diverse real-world communities. The literature on emergency water distribution system is limited by the following:

i. **Dependence on a single distribution system**

The literature predominantly focuses on a single emergency distribution system, such as PODs, mobile delivery, or direct delivery. For instance, Kim et al. (2021) optimized the locations of PODs but did not suggest alternative delivery methods. Similarly, Vieira et al. (2021) focused solely on water trucking without considering PODs. However, relying solely on one distribution system may not adequately meet the diverse needs of the population, highlighting a significant gap in addressing varied community needs (FEMA, 2022).

ii. **Failure to consider travel time data**

Studies often do not consider travel time data and instead solely use travel distance data when assessing accessibility. However, the role of travel distance is limited in predicting accessibility, and travel time is important for assessing individual accessibility (Weber and Kwan, 2002). Niedzielski and Boschmann (2014) point out that the relationship between travel distance and travel time sometimes reveals unusual and unexpected relations; for instance, longer distance can be covered by shorter travel time, and vice versa. As a result, considering not only travel distance but also travel time is crucial in reflecting individual accessibility. Additionally, the variation in travel time when using private vehicles versus public transportation is significant for a heterogeneous community with diverse mobility characteristics. However, the literature often overlooks this aspect due to a lack of relevant data (Kim et al., 2021).

iii. **Limited research scope from a spatial equality perspective**

Most studies assume equal mobility across populations from a spatial equality perspective. As a result, studies often do not consider mobility differences, such as varying availability of transportation options (Bian and Wilmot., 2018; Woo et al., 2021). However, solely focusing on spatial equality means that individual differences in access to emergency resources are ignored (Heil, 2022). This lack of consideration for spatial equity results in decreased accessibility, particularly for more vulnerable individuals.

Our study addresses the above research gaps in emergency water distribution by doing the following:

i. **Developing a hybrid method combining PODs and mobile delivery**

We propose a hybrid method that combines PODs with mobile delivery. By considering physiological status and socioeconomic status, we group the population and apply the proposed method. Furthermore, we conduct a sensitivity analysis to analyze the impact of the number of PODs opened on the resulting mobile delivery routing, as PODs serve as delivery depots. Interestingly, the results indicate that the number of PODs opened does not significantly impact VKT.

ii. **Incorporating both travel distance and travel time**

We incorporate travel distance (travel DBA) and travel time (travel TBA) to ensure spatial equality and equity simultaneously in addressing the emergency water distribution system across a heterogeneous community with differing mobility characteristics. Travel DBA is distance-based accessibility, which ensures equal access independent of population mobility, whereas travel TBA is time-based accessibility, considering different mobility (i.e., different transportation options). To do this, we specify origin and destination points and achieve estimated travel distance and travel time through the Google Maps API. Interestingly, our case study reveals unusual and unexpected relationships between travel distance and travel time. For example, although Block2 and Block3 have longer travel distance to C1 than Block1, they result in shorter travel time for any transportation option than Block1 (see Table 9). This indicates that road distance alone cannot fully capture the actual traffic experience. This example shows the importance of considering both travel distance and travel time in our case study.

Table 9. Example of an unusual and unexpected relationship between travel distance and travel time.

Origin (Block)	Destination (POD)	Travel distance (meters)	Travel time by private vehicle (seconds)	Travel time by public transportation (seconds)
Block1	C1	4,203	420	3,002
Block2	C1	4,549	392	2,661

Block3	C1	4,236	373	2,485

iii. Considering both spatial equality and spatial equity perspectives

Our method integrates spatial equality and spatial equity into emergency water distribution systems to increase accessibility to emergency water. The proposed model for POD locations limits the maximum travel distance for individuals to ensure spatial equality and minimizes travel time to maximize spatial equity. Specifically, we calculate the percentage of private vehicle ownership based on socioeconomic status. This helps predict the percentage of private vehicle and public transportation users and computes the travel time of the community. The proposed model reduces the average travel time by 7.05% and significantly decreases the worst travel time by 25.22% compared to the actual setup of nine PODs during the Flint, Michigan, water crisis. Additionally, the proposed mobile delivery model selects optimal routes for 20 trucks, based on the POD sites and block allocation results. Our method ensures equal and equitable access throughout the emergency water distribution system across a heterogeneous community.

7. Conclusions

We introduced a hybrid method for emergency water distribution planning and operation using PODs and mobile delivery, applied to the 2016 Flint, Michigan, water crisis. Our method prioritized spatial equality and spatial equity by considering the target population's physiological and socioeconomic status. The POD location-allocation model shows a 69.30% improvement in the objective function value and a 7.05% reduction in average travel time compared to actual POD assignments in Flint, with a 25.22% decrease in actual travel time for those with the longest travel time. The mobile delivery model, using 20 trucks over a total distance of 191.82 km, found a 16-foot truck to be the most cost-effective. Our study also noted that increasing the number of depots does not proportionally decrease the total VKT. Our hybrid approach effectively demonstrated how spatial equality and spatial equity can be improved in emergency water distribution systems. The outputs of our study can enhance emergency management systems by optimizing resource allocation and improving accessibility for vulnerable populations, ultimately leading to more efficient and equitable emergency response strategies.

8. Future Scope

Our study suggests potential directions for future research. First, it would be valuable to consider the potential traffic and congestion resulting from the selected PODs, as emphasized by Lee et al. (2009) and Kim et al. (2024), particularly in larger communities. Additionally, the availability of PODs for both short- and long-term durations can be taken into account, reflecting the variability in length of emergency responses. For example, in Flint, PODs operated over a two-year period from January 2016 to August 2018 (Heil, 2022). While FEMA suggests open areas as POD candidate locations, relying solely on existing community infrastructure (e.g., schools, athletic facilities, and community centers) and mass care facilities (e.g., shelters and food banks) might pose challenges for long-term operations. Considering the estimated duration of emergency distribution operations, different types of POD candidates could be designated, allowing these facilities to resume their original purposes during emergency responses. Lastly, the cost-benefit analysis for operating PODs can be expanded. Given the often-limited budgets/funds for emergency responses, which involve multiple tasks such as debris removal and emergency food/medical services, a comprehensive analysis of costs (POD staffing, equipment, and leasing/renting facilities if required) and benefits (operational efficiencies, user travel time, and emergency supply logistics from other facilities) is necessary to inform decision-making in emergency response planning.

9. Data Availability Statement

The following data are available from Dr. Jooho Kim (jooho.kim@tamu.edu) upon reasonable request.

- Past and new locations of points of distribution
- Road network
- Census block data
- City zoning data

- Origin-destination matrix
- School locations
- Python codes for the proposed method

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