Evacuation Destination Assignment using PostgreSQL with PostGIS, and pgRouting for Wildfire Evacuation: A Spatial Database Approach

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INTRODUCTION

The wildland-urban interface (WUI) refers to a region where human-made structures and residential developments mix with undeveloped wildland or vegetative fuels (Radeloff et al., 2005). WUI is more susceptible to wildfires due to flammable materials and the presence of humans (Siam et al., 2022). When a WUI wildfire occurs, it can quickly ignite a considerable number of homes in a short time period (Radeloff et al., 2018)

. WUI fires pose a serious risk to

Protective actions help to reduce wildfire threats and increase public safety. The most common protective action recommendations (PARs) issued by incident commanders (ICs) are shelter-in-place or evacuation (Cova et al., 2017; Li et al., 2019). In the U.S., evacuation is the most common PAR in wildfires (Cohn et al., 2006).

Effective evacuation planning and management are crucial for enhancing public safety and restoring community functionality (Bayram & Yaman, 2018). Recently, many studies have focused on wildfire evacuations, emphasizing the need to carefully model each step of the evacuation process (Cova et al., 2024). Among these steps, destination choice is particularly important in traffic simulation modeling and, thereby, evacuation planning. This is because the output from this step is input to the traffic assignment step. In addition to that, destination choice is necessary for network congestion assessment and delay assessment (Cheng et al., 2008). Despite its importance, there is a lack of studies focusing on destination selection (Kuligowski, 2021). Evacuee destinations can include multiple stops along a trip, meaning evacuees may have more than one destination (Cova et al., 2024). Southworth (1991) identified four methods for modeling evacuee destination choices. These include heading to the nearest destination based on distance or travel time and choosing exit points influenced by proximity to friends, relatives, or hazard onset speed. Other methods involve following pre-specified destinations in an evacuation plan or selecting routes based on real-time traffic conditions. Among these four methods, the first assumption is more suitable for small communities, particularly when the hazard is progressing slowly, and evacuees have the option of staying with relatives or seeking shelter elsewhere. The third method, which involves assigning pre-determined destinations can be used to direct residents from specific areas to designate exits. With well-developed plans and effective traffic management, this approach can yield highly efficient outcomes.

During evacuation planning, destination selection from destination choices can be done using various methods. When the available destination choices and their locations are known, spatial interaction models can be used for destination selection (Southworth, 1991). These models assess the attractiveness of each destination based on factors such as the number of available beds, the ability to accommodate pets, or the availability of medical staff. Additionally, some studies focused on selecting nearest destination from predefined shelter locations (Beloglazov et al., 2016; Grajdura et al., 2020). However, in situations where spatial data for directing evacuees to specific shelter locations is limited, evacuation destinations can be determined based on egresses located farthest from the fire front. Most previous studies have assigned the nearest egress point to each evacuee during the destination selection step (Li, 2022; Li et al., 2019). However, based on the evacuation route system configuration and home distribution, it can lead to the overuse of some egresses and create traffic congestion around some egresses (Li, 2022). Therefore, there is a pressing need to explore methods for destination selection methods that can improve the utility of evacuation route system and egresses.

Zone-based approaches can simplify evacuation planning by assigning evacuees from designated zones to specific destinations, rather than focusing on individual destination selection. In this method, the at-risk area is divided into distinct zones, and all evacuees within a zone are directed to a common destination. Each zone can also be further subdivided, with subgroups assigned to different egress routes. However, when dividing the at-risk area, it is essential to establish clear and well-defined boundaries to prevent confusion among evacuees about which group they belong to (Lindell et al., 2018). To avoid miscommunication, the official evacuation warning system used by the county in the at-risk area can be employed. In this study we considered Genasys zones which are provided by Genasys Inc (Genasys Inc. (NASDAQ: GNSS), 2022; genasys Protect; Genesys Cloud Resource Center). These zones were chosen because many counties in California rely on Genasys zones to issue PARs during emergencies. When further, subdividing the Genasys zones, geographic boundaries (e.g., rivers) or social groups within Genasys zones can be used (e.g., primary homes and mobile homes) (Lindell et al., 2018).

Egress assignment using zone-based approach can be supported through the use of spatial databases (Zhou et al., 2010). Spatial databases provide a structured framework for managing and analyzing geospatial data, making them ideal for addressing the challenges associated with evacuation planning. Spatial databases can also be accessed through Java libraries for desktop evacuation modeling applications and JDAL databases during web application modeling. PostgreSQL is a widely known open-source relational database management system (RDBMS) which can be extended with PostGIS to enable advanced geospatial capabilities (Pulis & Attard, 2008). Additionally, tools like pgAdmin offer a user-friendly interface for managing PostgreSQL databases, allowing for visualization, querying, and analysis of geospatial data during egress selection. Therefore, this study focuses on utilizing the pgAdmin framework to store, query, and visualize spatial data within a PostgreSQL database, facilitating destination selection through a zone-based approach.

RESEARCH QUESTIONS

The goal of this study is to determine the closest egress for each Genasys zone using spatial database approach. Furthermore, this study aims to subdivide the Genasys zones based on the social groups present within each zone. Specifically, the objective is to assign the closest egress for all evacuees within each Genasys zone using a zone-based approach by calculating path costs along a road network with the Dijkstra algorithm. To fulfill these research objectives, the study addresses the following research questions:

1. How can egress be assigned for each Genasys zones according to improve the utility of all available the egresses?
2. How do social group considerations impact the zone-based egress selection?

DATA COMPILATION

We used the Tahoe Donner neighborhood in the Town of Truckee, California as our study area. Tahoe Donner is a resort community which is located within WUI. As shown in Figure 1, ICs in Tahoe Donner used Genasys zones to issue PARs through different channels such as television, phone calls, text messages, and social media (Nevada County California). Tahoe Donner contains ten Genasys zones. This community has two evacuation egresses, and these egresses are Alder Creek Rd and Northwoods Blvd. Due to limited egress options and transient populations, Tahoe Donner can face significant wildfire evacuation challenges.

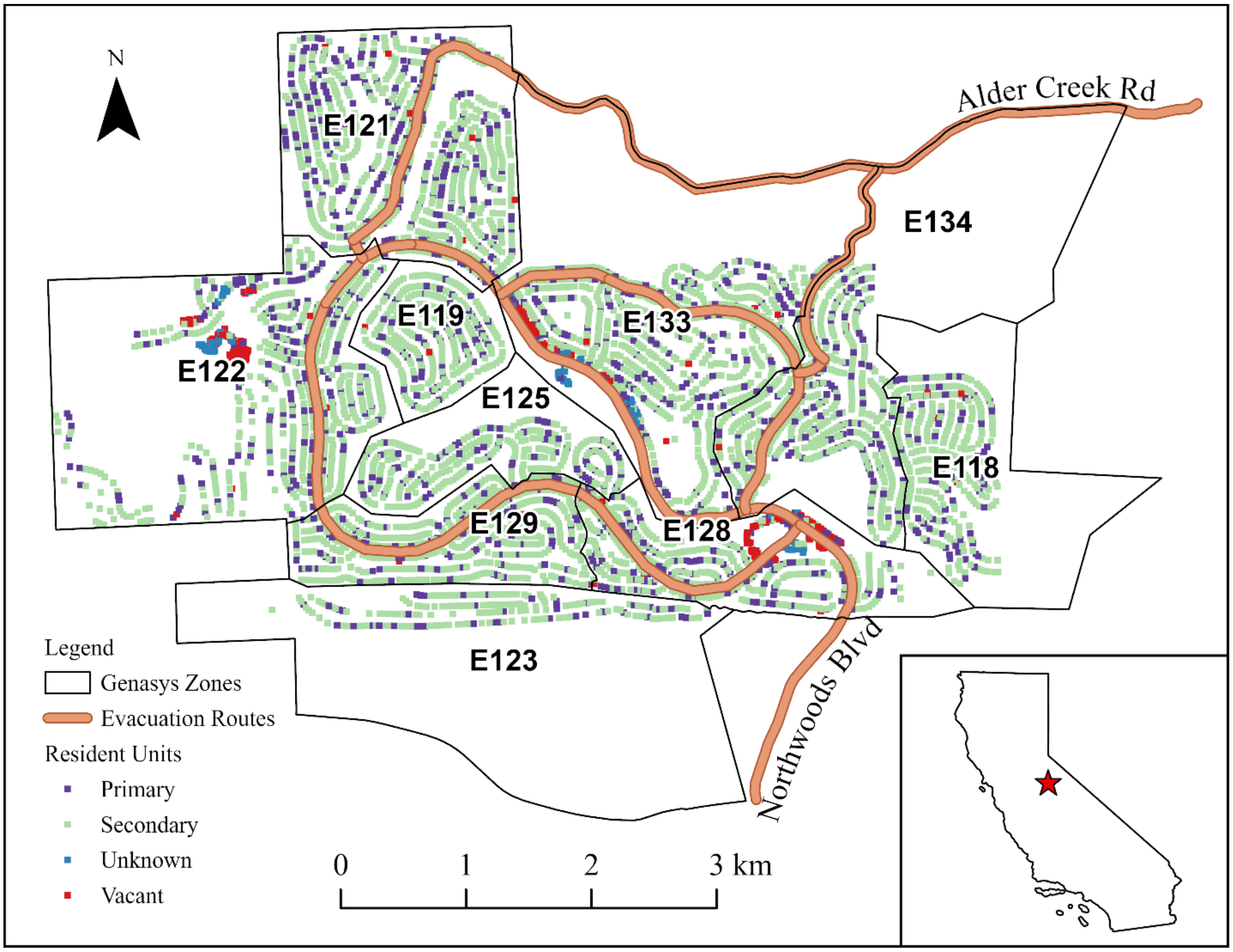

Figure 1. The map of the Tahoe Donner community.

We employed the spatial datasets listed in Table 1 to develop a spatial database and perform analysis. The residential parcel data and Genasys zones obtained from Nevada County are in the shapefile format. Residential parcel data contains the household locations and the occupancy type of these houses. Tahoe Donner has 5,858 residential parcels, and about 70% of the parcels are secondary homes. The availability of second homes in resort WUI communities adds uncertainty about occupancy during a wildfire event (Li, 2022). We compiled the road data from OpenStreetMap (OSM) and refined it using Java OpenStreetMap editor (JOSM) software to derive the roads designated for vehicular traffic (e.g., private vehicles). This road dataset is essential for identifying the nodes and links of the road network.

Table 1. The primary datasets which were used for this study.

Dataset	Source	Year
Residential parcel data	Nevada County Assessor's Office	2019
Genasys zones	Nevada County	2019
Road data	OpenStreetMap	2019

Table 2 shows the occupancy type and population information for each Genasys zone. In Tahoe Donner, each Genasys zone has a higher number of second homes compared to primary homes.

Table 2. Occupancy type and population information for the Genasys zones.

Genasys zone	Occupancy Type				Total Households	Estimated Population
	Primary	Secondary	Unknown	Vacant		
E122	192	532	98	121	943	483
E121	238	654	-	7	899	621
E129	101	469	-	2	572	262
E134	119	455	-	3	577	379
E133	195	666	64	72	997	639
E125	67	260	-	2	329	176
E119	56	278	-	-	334	170
E118	75	301	-	4	380	241
E128	145	342	43	84	614	305
E123	41	172	-	-	213	530
Total	1229	4129	205	295	5858	3,806
Percent (%)	21.0	70.5	3.5	5.0	100.0	

SPATIAL DATABASE DESIGN

Figure 2 shows the spatial database design of the study. This was designed in the pgAdmin framework using PostGIS extension. This spatial database design integrates key entities such as Genasys zones, residential parcels, and road to create new tables (e.g., destinations, SourceNodes, DestinationNodes, and Egress).

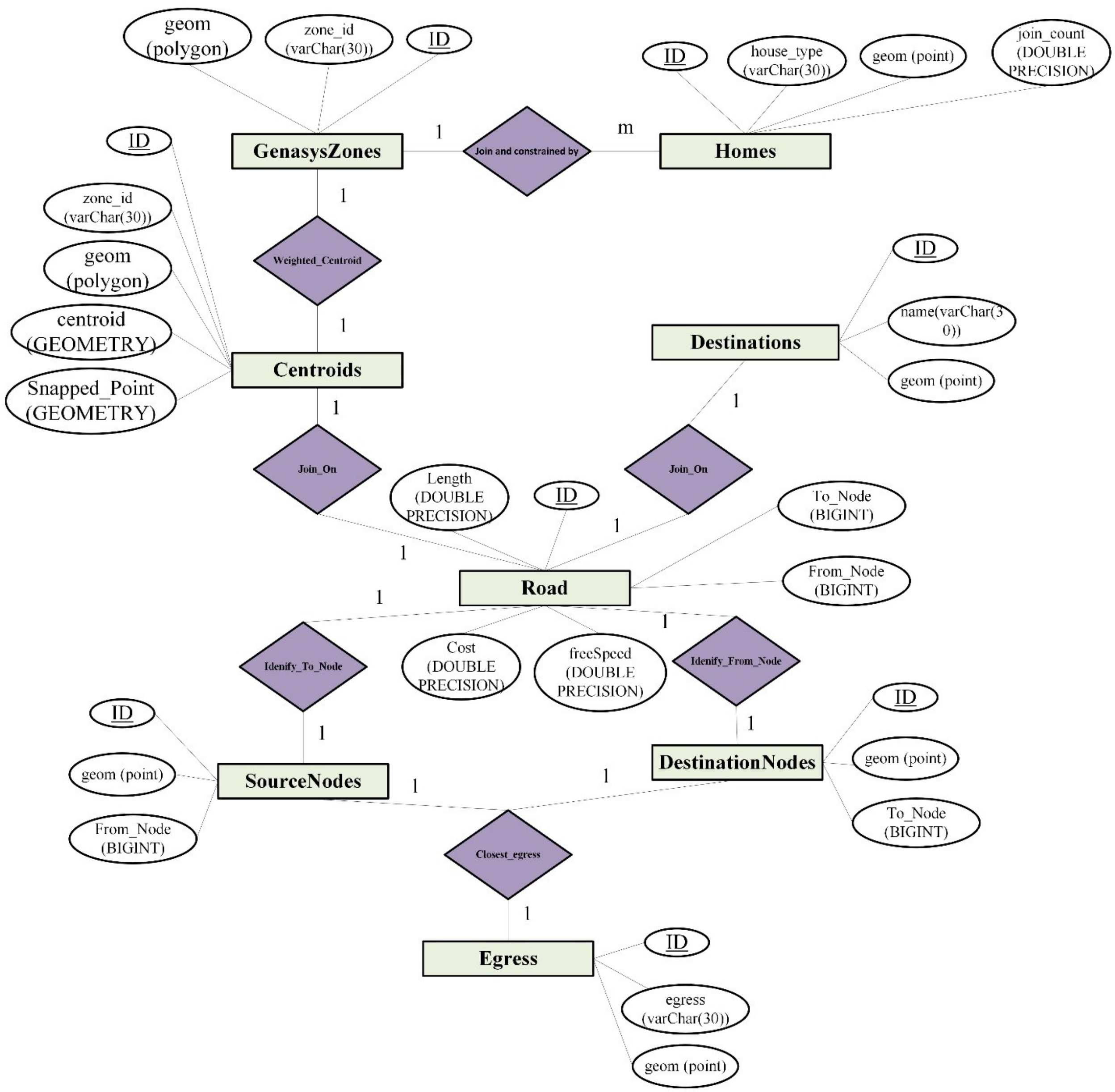

Figure 2. Spatial database design of the study

SPATIAL DATABASE IMPLEMENTATION

This study implemented a spatial database schema to determine the nearest egress points for evacuees. Figure 3 shows the proposed methodology of the study. The first step involved identifying the origin of each trip. Since we assumed that all evacuees within a Genasys zone evacuate to the same destination, the centroid of each zone was used as the trip origin. This simplification allows for efficient calculation of the closest destination for all evacuees within each zone. However, since homes are not uniformly distributed across Genasys zones, the centroids were constrained to areas containing homes using the `ST_Contains` function. Home locations within each Genasys zone were aggregated with the `ST_Collect` function, and the weighted centroids were calculated using `ST_Centroid`. These centroids were then snapped to the nearest points on the road network using the `ST_ClosestPoint` function. The to_node of the road links containing the weighted centroids was identified, connecting each zone to the road network. The second step involves identifying the destinations for evacuation. The study area had two egress points serving as destinations for evacuees, which were mapped onto the road network. Each egress point was linked to its corresponding road segment using the `from_node`. In the third step, road link costs were calculated as time, based on their length and speed limit (e.g., length/speed limit). The shortest paths from the to_node of the snapped centroids (sources) to the from_node of the egress points (targets) was then calculated using the pgr_dijkstra function, which accounted for road link costs. Each zone was assigned to the closest egress point based on the lowest total cost. Finally, the results were validated against outputs from the closest facility function in ArcGIS Pro software, ensuring consistency and reliability of the methodology.

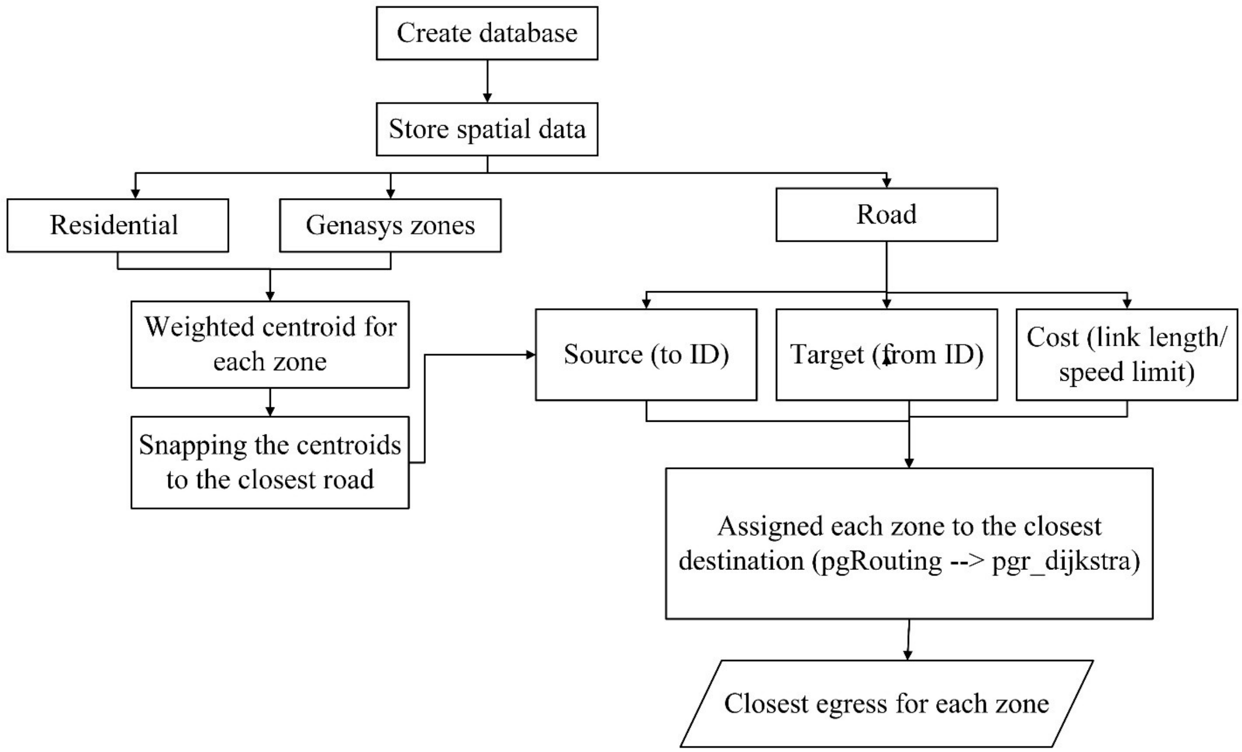

Figure 3. Flowchart for proposed method of egress selection for each Genasys zone

In the previous method, zone-based egress points were assigned as destinations for all evacuees within a Genasys zone. In contrast, the second methodology introduced a more refined approach, where destinations were assigned based on social groups within each Genasys zone. Figure 4 illustrates the proposed methodology for this approach. It was assumed that each Genasys zone contains two social groups: second homeowners and other homeowners. In this study, second homeowners were considered as one social group because approximately 70% of homes in the community are second homes. All other types of homes, including primary homes, unknown occupancy, and vacant properties, were grouped into a second category. Egress assignments for each social group were carried out by proportionally distributing evacuees across the available egresses. This proportional allocation aimed to increase the utility of each egress while reducing the risk of overwhelming any single egress, ensuring a more balanced and efficient evacuation process.

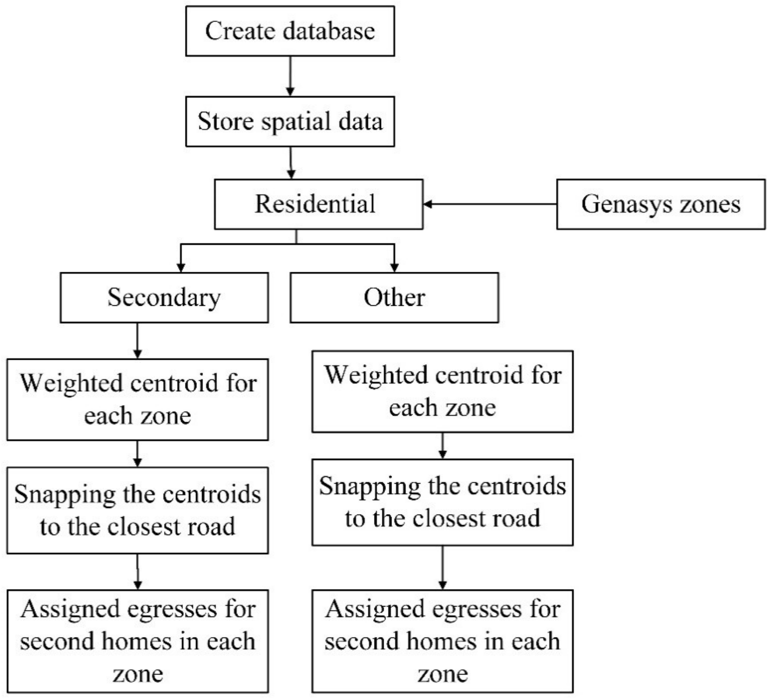

Figure 4. Flowchart for proposed methodology of egress selection for second and other homeowners for each Genasys zone

ANALYSIS

Figure 5 presents the results for the centroids of each Genasys zone, constrained by home locations. Figure 6 displays the results for weighted centroids, which are snapped to the nearest point on the road network. I realized that finding the weighted centroids and snapping them to the closest points on the road is easier using a spatial database approach compared to utilizing ArcGIS Pro software.

Figure 5. Weighted centroid of each Genasys zone.

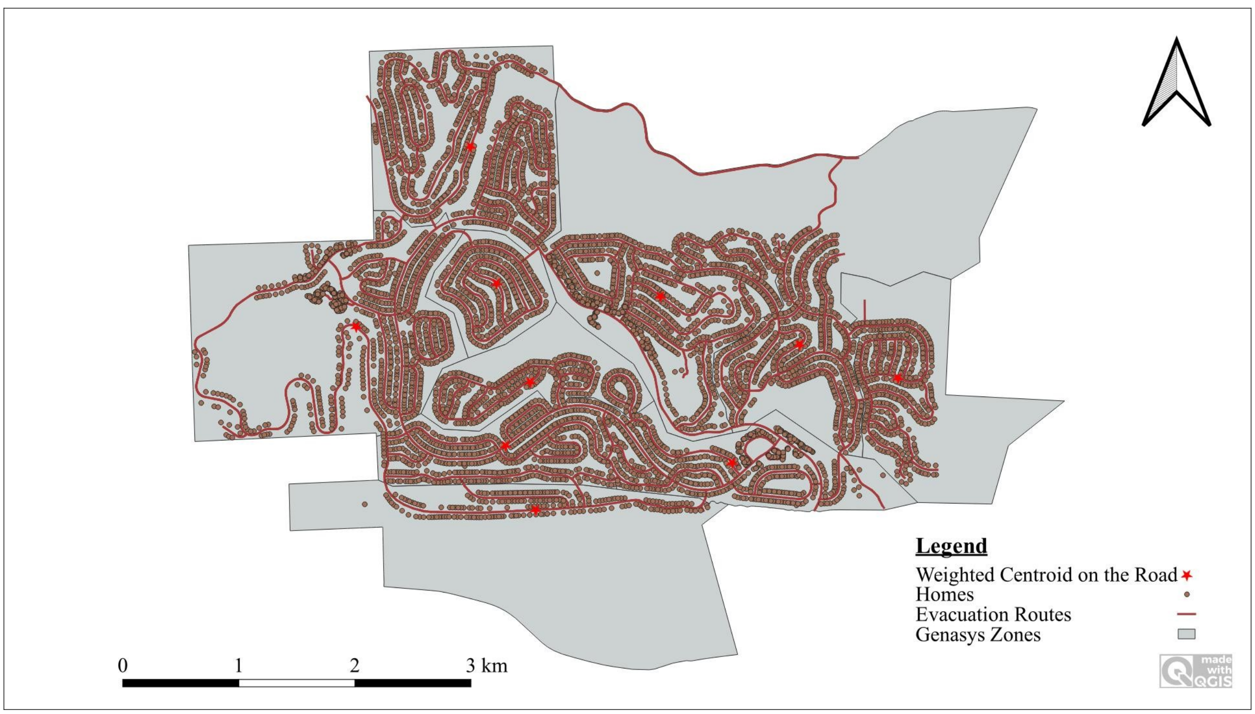

Figure 6. Snapped the weighted centroid of each Genasys zone to the closest point on the road.

Figure 7 presents the calculated egress points for each Genasys zone, while Figure 8 displays the results obtained using the Closest Facility function in ArcGIS Pro. A comparison of the two figures confirms that the results are identical, validating the accuracy of the calculations. It is observed that only Genasys zone E121 utilizes egress A, whereas all other zones use egress B. This uneven distribution may lead to overuse of egress B, causing congestion and higher traffic density in its vicinity. Such an allocation is not effective and highlights the need for a more balanced approach to egress selection.

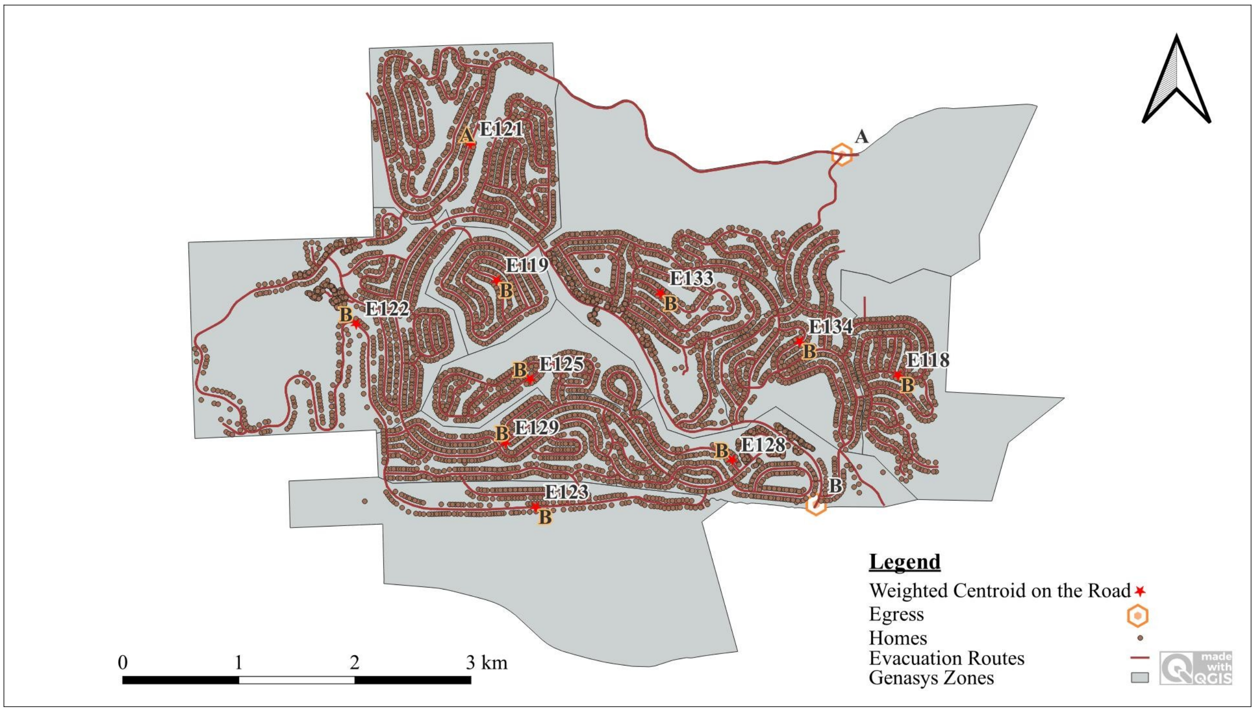

Figure 7. Closest egress for each Genasys zone.

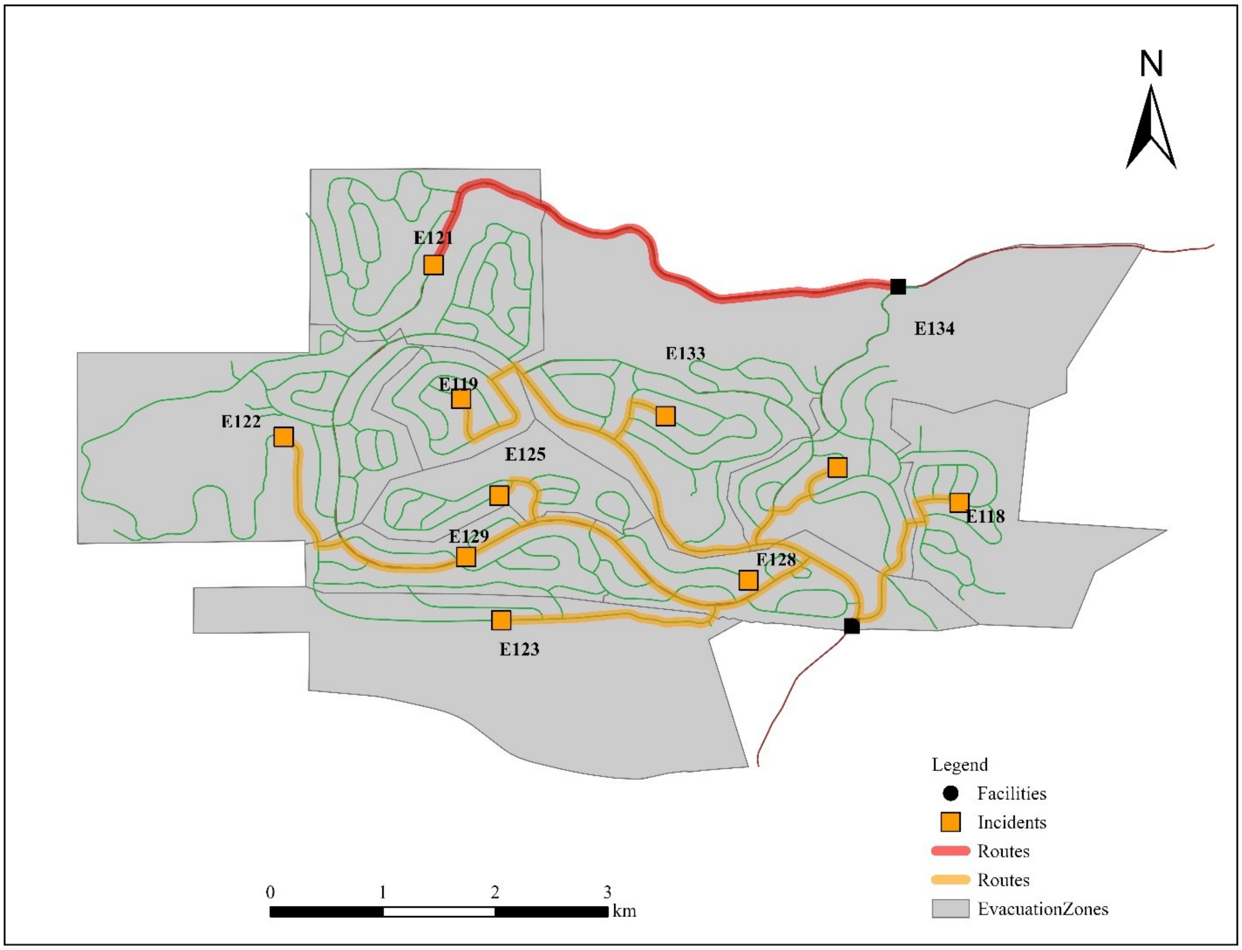

Figure 8. Results of egress selection using ArcGIS Pro for validation purpose.

Figure 9 illustrates the results of egress selection for second homes and other types of homes within each Genasys zone. In this scenario, a total of 2,125 homes utilizes egress A, while 1,726 homes use egress B. Among second homes, 1,764 are assigned to egress A, and 2,365 are assigned to egress B. This method of egress selection is much prominent than the previous method.

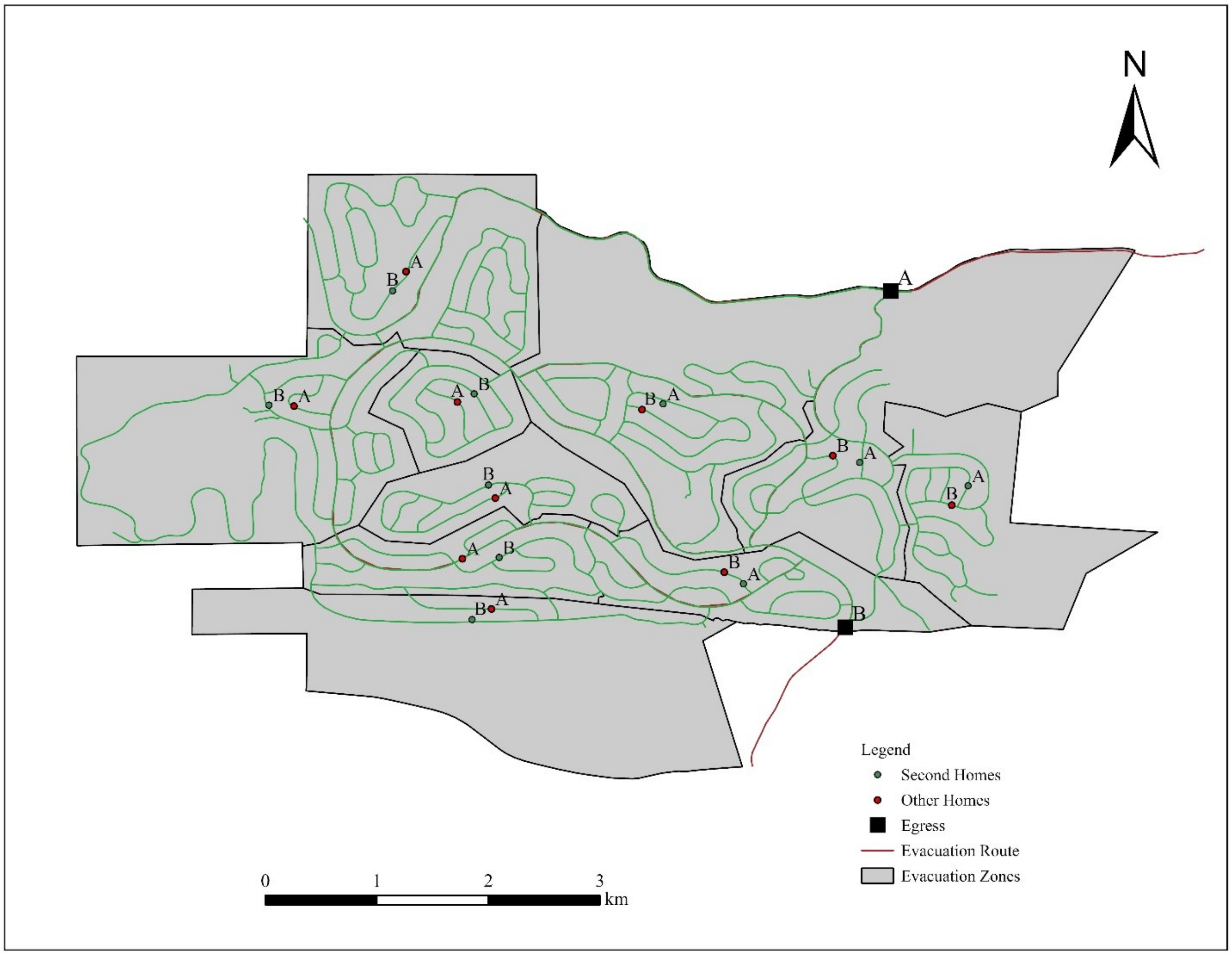

Figure 9. Egress selection for second homes and other home types of each Genasys zone.

CONCLUSION

This study presents two distinct methodologies for the selection of egresses during wildfire evacuation within specified Genasys zones. The first methodology focuses on identifying the nearest egress point for each Genasys zone based on calculated travel time. This ensures that all evacuees within each Genasys zone are assigned to a single egress. The second methodology focuses on assigning specific egresses to various social groups within each Genasys zone. This approach aims to enhance the utility of egress points. The key contributions of this research are as follows. Firstly, the study considers Genasys zones as the evacuation zoning system when performed zoned-based destination selection. Therefore, results of this study can clearly communicate between emergency officials and evacuees. Such clarity is important in reducing confusion and ensuring a coordinated response during high-pressure situations. Secondly, the consideration of social groups within each Genasys zone demonstrates the capability to implement partial evacuations. Furthermore, this approach emphasizes the potential to account for evacuation decision-making differences between various groups. Additionally, this study proposes multiple methods for selecting evacuation egresses pertinent to each Genasys zone. However, the effectiveness of these methods is dependent on the configuration of evacuation routes. Therefore, it is essential to explore various options to improve the utility and accessibility of egress points. In conclusion, this case study highlights the considerable benefits of assigning designated egress points for each Genasys zone and social groups within them. The findings may serve as a valuable resource for ICs in refining their evacuation planning strategies. Furthermore, future research could enhance these methodologies by incorporating iterative approaches for assigning egress points, informed by real-time data and the current conditions of road networks.

REFERENCES

Bayram, V., & Yaman, H. (2018). Shelter location and evacuation route assignment under uncertainty: A benders decomposition approach. *Transportation science*, *52*(2), 416-436.

Beloglazov, A., Almashor, M., Abebe, E., Richter, J., & Steer, K. C. B. (2016). Simulation of wildfire evacuation with dynamic factors and model composition. *Simulation Modelling Practice and Theory*, *60*, 144-159. https://doi.org/https://doi.org/10.1016/j.simpat.2015.10.002

Cheng, G., Wilmot, C. G., & Baker, E. J. (2008). A destination choice model for hurricane evacuation. proceedings of the 87th annual meeting transportation research board, Washington, DC, USA,

Cohn, P. J., Carroll, M. S., & Kumagai, Y. (2006). Evacuation behavior during wildfires: results of three case studies. *Western Journal of Applied Forestry*, *21*(1), 39-48.

Cova, T. J., Dennison, P. E., Li, D., Drews, F. A., Siebeneck, L. K., & Lindell, M. K. (2017). Warning triggers in environmental hazards: Who should be warned to do what and when? *Risk analysis*, *37*(4), 601-611.

Cova, T. J., Sun, Y., Zhao, X., Liu, Y., Kuligowski, E. D., Janfeshanaraghi, N., & Lovreglio, R. (2024). Destination unknown: Examining wildfire evacuee trips using GPS data. *Journal of Transport Geography*, *117*, 103863. https://doi.org/https://doi.org/10.1016/j.jtrangeo.2024.103863

Genasys Inc. (NASDAQ: GNSS). (2022). *Genasys Inc. Adds Four More California Counties to Zonehaven Evacuation Management Contracts*. Retrieved July 29 from https://genasys.com/press-releases/genasys-inc-adds-four-more-california-counties-to-zonehaven-evacuation-management-contracts/

genasys Protect, f. Z. A. Retrieved July 29 from https://protect.genasys.com/search

Genesys Cloud Resource Center. *Automatic time zone mapping overview - Genesys Cloud Resource Center*. Retrieved October from https://help.mypurecloud.com/articles/automatic-time-zone-mapping-overview/

Grajdura, S. A., Borjigin, S. G., & Niemeier, D. A. (2020). Agent-based wildfire evacuation with spatial simulation: a case study. Proceedings of the 3rd ACM SIGSPATIAL International Workshop on GeoSpatial Simulation,

Kuligowski, E. (2021). Evacuation decision-making and behavior in wildfires: Past research, current challenges and a future research agenda. *Fire Safety Journal*, *120*, 103129.

Li, D. (2022). A data-driven approach to improving evacuation time estimates during wildfires for communities with part-time residents in the wildland-urban interface. *International Journal of Disaster Risk Reduction*, *82*, 103363. https://doi.org/https://doi.org/10.1016/j.ijdrr.2022.103363

Li, D., Cova, T. J., & Dennison, P. E. (2019). Setting wildfire evacuation triggers by coupling fire and traffic simulation models: a spatiotemporal GIS approach. *Fire Technology*, *55*, 617-642. https://doi.org/https://doi.org/10.1007/s10694-018-0771-6

Lindell, M. K., Murray-Tuite, P., Wolshon, B., & Baker, E. J. (2018). *Large-scale evacuation: The analysis, modeling, and management of emergency relocation from hazardous areas*. CRC Press.

Nevada County California. *Evacuation Zones*. Retrieved July 29 from https://www.nevadacountyca.gov/3223/Evacuation-Zones

Pulis, M., & Attard, M. (2008). Exploring the shortest route options: applying environmental indicators to calculating shortest route.

Radeloff, V. C., Hammer, R. B., Stewart, S. I., Fried, J. S., Holcomb, S. S., & McKeefry, J. F. (2005). The wildland–urban interface in the United States. *Ecological applications*, *15*(3), 799-805.

Radeloff, V. C., Helmers, D. P., Kramer, H. A., Mockrin, M. H., Alexandre, P. M., Bar-Massada, A., Butsic, V., Hawbaker, T. J., Martinuzzi, S., & Syphard, A. D. (2018). Rapid growth of the US wildland-urban interface raises wildfire risk. *Proceedings of the National Academy of Sciences*, *115*(13), 3314-3319. https://doi.org/https://doi.org/10.1073/pnas.1718850115

Siam, M. R. K., Wang, H., Lindell, M. K., Chen, C., Vlahogianni, E. I., & Axhausen, K. (2022). An interdisciplinary agent-based multimodal wildfire evacuation model: Critical decisions and life safety. *Transportation Research Part D: Transport and Environment*, *103*, 103147. https://doi.org/https://doi.org/10.1016/j.trd.2021.103147

Southworth, F. (1991). Regional evacuation modeling: A state-of-the-art review.

Szasdi-Bardales, F., Shamsaei, K., Lareau, N. P., Juliano, T. W., Kosovic, B., Ebrahimian, H., & Elhami-Khorasani, N. (2024). Integrating dynamic wildland fire position input with a community fire spread simulation: A case study of the 2018 Camp Fire. *Fire Safety Journal*, *143*, 104076. https://doi.org/https://doi.org/10.1016/j.firesaf.2023.104076

Zhou, X., George, B., Kim, S., Wolff, J. M., Lu, Q., Shekhar, S., & Nashua, O. (2010). Evacuation Planning: A Spatial Network Database Approach. *IEEE Data Eng. Bull.*, *33*(2), 26-31.