GIS-based Flood Risk Assessment of Greater Glasgow, Scotland

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Declaration/Signed Statement:

"We declare the following work is our own and, where the work of others has been used, it has been clearly identified".

Abstract

Flooding is a well-documented phenomenon in Glasgow, Scotland, as evidenced by historical records and literature. To further assess the potential risk of pluvial flood and provide an integrated surface water flood risk map in Greater Glasgow, this technical report displays the results of a GIS-based risk analysis.

The study utilises three modules of vulnerability, exposure and hazard to calculate the risk, but it must be noted that each layer is limited to three factors and the flood risk extent presented is therefore not exhaustive. The analysis incorporates information on Landsat satellite images of 2022 to represent land usage (NDVI), surface water flood extent risk, slope, buildings and roads, the existence of fire stations, and the 2011 census for population density, limited mobility and deprivation.

The findings indicate that the hazard is most pronounced in the northern regions of Greater Glasgow and outside of Glasgow City. Despite the lower hazard levels within Glasgow City, the high levels of exposure and vulnerability result in an elevated overall flood risk. For this reason, the report recommends targeting flood mitigation measures in Glasgow City as the area presents the highest level of risk. There are several limitations to this study that could be addressed in future research such as incorporating additional variables that influence surface water flood risk such as sewer systems and critical infrastructure. Furthermore, updating the analysis with 2022 census data once available would provide a more comprehensive understanding of the risk.

Keywords: flood risk; Greater Glasgow; flood vulnerability; flood hazard; flood exposure; risk mapping, surface water flood

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1. Introduction

The project deals with flood risk stemming from pluvial sources in Greater Glasgow, Scotland. Since the historical record of floods in this area is significant, a thorough analysis of flooding risk by means of spatial data analysis is paramount to reduce vulnerability and increase resilience in the future. The project is limited to nine factors that influence risk and have adequate data availability.

The main aims of this investigation are:

1. To identify key variables contributing to surface water flood risk in Greater Glasgow;
2. To analyse the main determinants of surface water flood risk;
3. To produce an integrated surface water flood risk map and identify where flood mitigation measures should be placed.

Based on these aims, the following research question guides this project:

How is surface water flood risk distributed in Greater Glasgow, and where should flood mitigation measures be targeted in the region?

2. Methodology

a. Context of Flood Risk in Greater Glasgow

For the purpose of the study, flooding within Greater Glasgow was selected as the hazard context and study area (Figure 1) due to the region's documented history of pluvial floods in 1993, 2002 and 2013 (Paudel, 2022). Scotland's Greater Glasgow encompasses Glasgow City and its surrounding municipalities, forming a conurbation with about 1.2 million inhabitants (Glasgow Centre for Population and Health, n.d.). Despite its hilly geography, Glasgow has a relatively low elevation with a maximum elevation of 200 meters above sea level (Glasgow City Council, 2020).

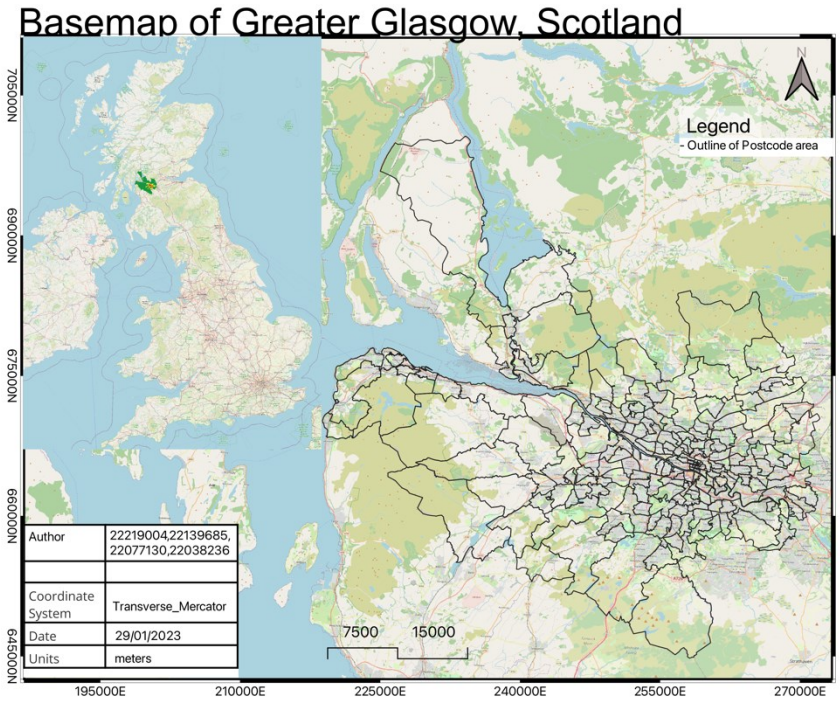

Figure 1: Map of Greater Glasgow divided into its postcode areas

Surface water floods induce on average 30% of annual damages (SEPA, 2015) in the Clyde and Loch Lomond Local Plan District. The proximity to watercourses and an average of over 180 days of rainfall annually (1991-2020) (Met Office, 2022) are key contributing factors to flood hazard. Given the intensification of climate change-related phenomena, flooding in Glasgow can be expected to worsen (Adaptation Scotland, 2017; Majekodunmi et al., 2020).

Apart from high and potentially rising hazard risk, certain vulnerability factors exacerbate Glasgow's flood risk and are a subject of interest. The case study captures Majekodunmi et al.'s (2020) finding of "significant inequality associated with economic decline" in Glasgow City by analysing deprivation levels, people's limitations in day-to-day activities, and access to fire brigade emergency services. However, it should be noted that the study does not examine the historical contribution of overwhelmed sewer systems in increasing flood vulnerability (Cole et al., 2016) due to the unavailability of relevant data.

b. Data Collection and Data Sources

The flood risk map for Greater Glasgow was produced using nine layers, equally divided between hazard, exposure, and vulnerability. Data for these layers was gathered from various online open-access sources (Table 1) and processed using the software QGIS 3.28.2-Firenze and ArcGIS 10.3.1.

Table 1: Overview of data sources for each layer

	Layer 1	**Layer 2**	**Layer 3**
Hazard	NDVI GloVis Landsat 8-9 (2022)	Slope via line density of elevation Ordnance Survey Terrain 50 (2022)	Surface water flood extent Scottish Environment Protection Agency SEPA Flood Map Version 2.0 (2022)
Exposure	Population density Scotland's Census (2011)	Road density Ordnance Survey Open Roads (2022)	Building density OCHA Services - HOTOSM UK Scotland Buildings (2020)
Vulnerability	Deprivation Scottish Government – Scottish Index of Multiple Deprivation (2020)	Fire stations Scottish Fire and Rescue Service (2023)	Limited mobility Scotland's Census (2011)
Greater Glasgow shapefile: The University of Edinburgh – Edinburgh Data Share (2012)			

c. Data Analysis Methods: Preparation of Hazard, Exposure and Vulnerability Layers (QGIS)

Layers were rasterized, reprojected to WGS1984 UTM Zone 30 N, reclassified and extracted by mask according to an NDVI base layer, and/or resampled (if necessary) to have the same number of columns/rows and cell size.

All layers, except for NDVI and slope, are aligned with Greater Glasgow's postcode areas, meaning that the resolution of the respective data is consistent.

i. Hazard Layers

Surface water flood extent

The layer “surface water flood extent in Greater Glasgow” (Figure 2) displays the probable extent of potential surface flooding for catchments greater than 3 km^2. SEPA provides national data for high, medium and low flood probability (10-, 200- and 1000-year return period) and their extent, respectively.

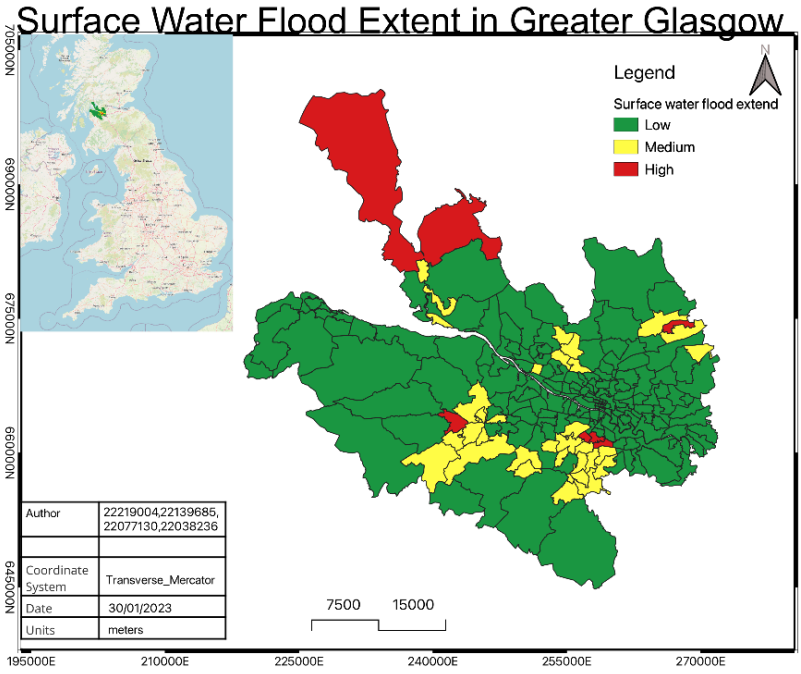

Figure 2: Map of probable surface water flood extent in Greater Glasgow

Slope

For the slope layer (Figure 3), multiple tiles for elevation were merged into one layer, and then the density of the elevation lines was calculated showing the steepness, and hence the influence of the extent and velocity of water dissemination downhill.

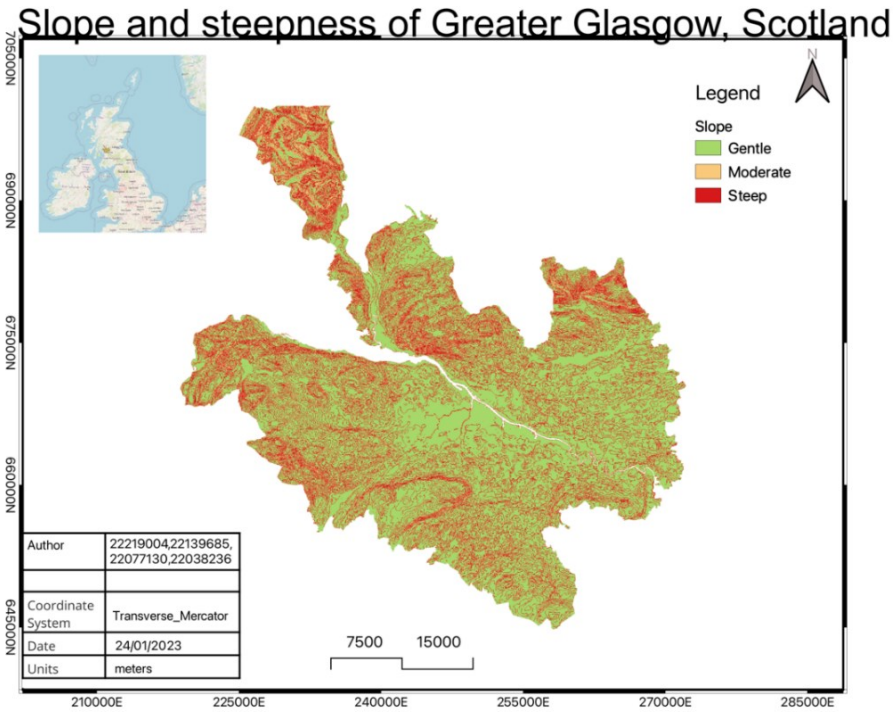

Figure 3: Map of slope and steepness of Greater Glasgow

Normalised Difference Vegetation Index (NDVI)

NDVI accounts for the volume and rate of water runoff. The layer (Figure 4) was calculated from Bands 5 and 4 of the Landsat 8-9 satellite image from 2022 using the following formula:

$$\frac{(Band\ 5 - Band\ 4)}{(Band\ 4\ +\ Band\ 5)}$$

After the calculation, the NDVI was classified into four categories (Table 2) and matched with OSM and ESA world cover (ESA, 2021).

Table 2: NDVI classification

Land Cover	Description
Waterbody	Permanent waterbodies like rivers, lakes, sea
Built-up area	Infrastructure and sealed surfaces
Vegetation	Grassland, agricultural areas, parks and gardens
Tree cover	Area covered by trees

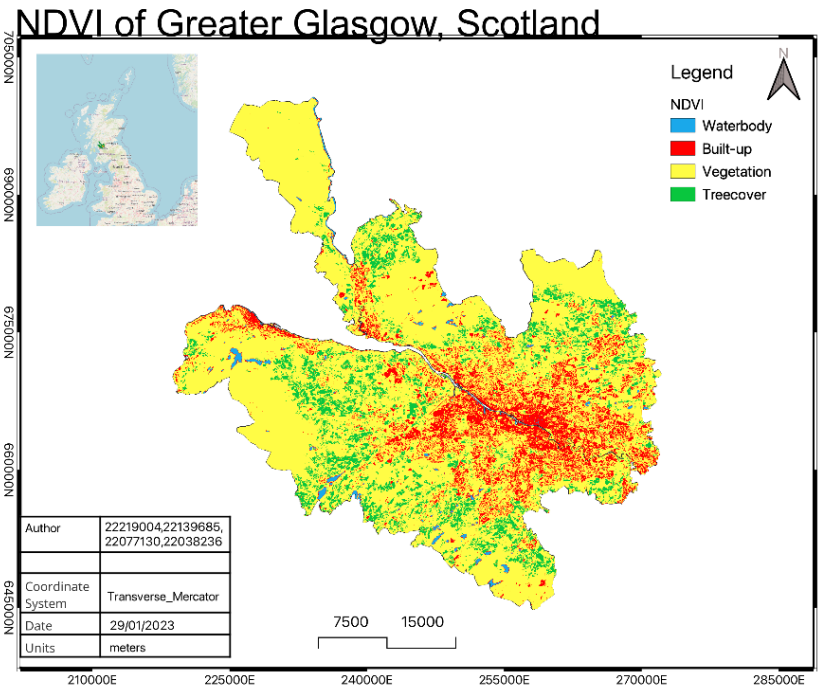

Figure 4: Map of NDVI of Greater Glasgow

ii. Exposure Layers

Population density

Population density (Figure 5) was calculated using population data according to the 2011 census and postcode area. The highest population density is situated in the city centre, resulting in an elevated pressure on drainage systems, thus increasing flood possibility and the pressure on emergency services and planners.

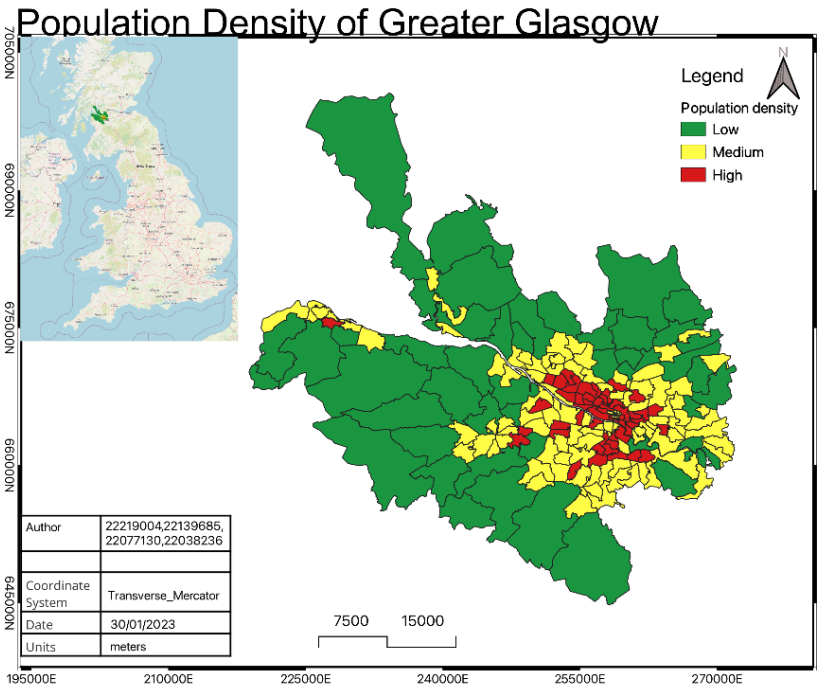

Figure 5: Map of population density in Greater Glasgow

Building density

Buildings are crucial parts of infrastructure. Therefore, their presence in flood prone areas must be accounted for (Figure 6). If affected by floods, the need for temporary accommodation, and economic and social impacts e.g., closed businesses and schools, should be expected. Consequently, flooding of buildings is not only disadvantageous for residents, but also for the broader society and vulnerable groups. In this analysis, the existence of a basement, insurance state and building type are unaccounted for. The highest building density can be found in the city centre.

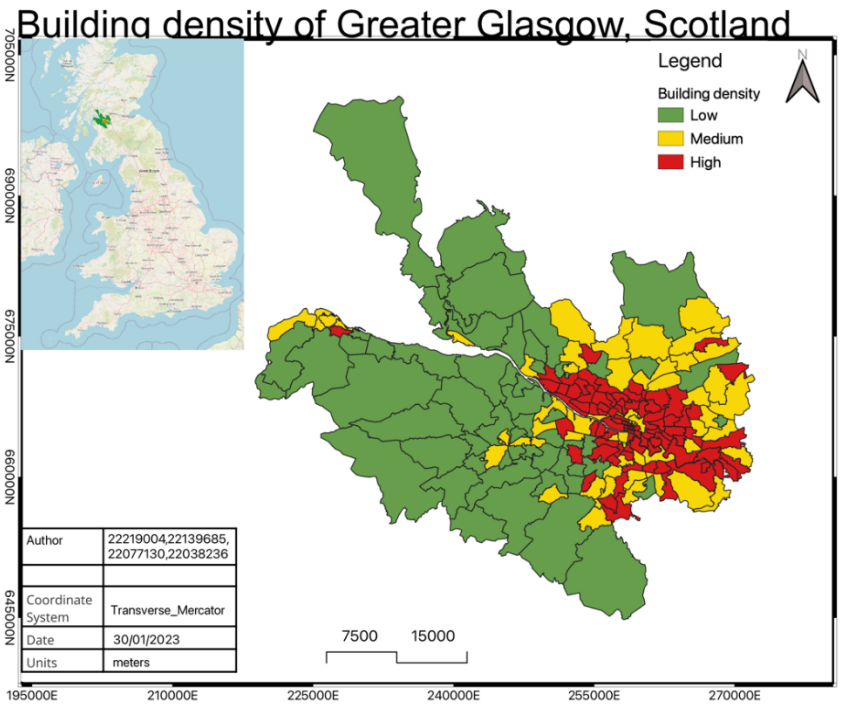

Figure 4: Map of building density in Greater Glasgow

Road density

Roads are a crucial component of infrastructure as they facilitate mobility, including access to emergency services/healthcare, and are therefore a vital part of the exposure module (Figure 5). The distribution of road lengths was determined according to the postcode, enabling the calculation of density. Again, the higher the density, the higher the exposure to flood. The highest risk is mainly concentrated within Glasgow City.

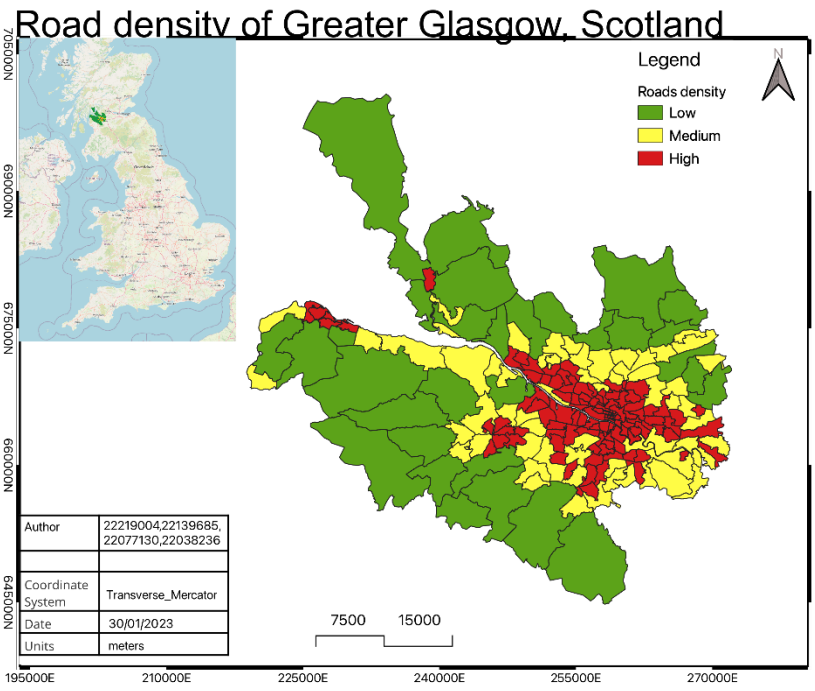

Figure 5: Map of road density in Greater Glasgow

iii. Vulnerability Layers

Deprivation

We account for deprivation since "people from areas classed as more deprived disproportionally face more flood risk than those living in less deprived areas" (Environment Agency, 2022). The layer (Figure 8) is composed of various indicators (Table 3) that relate to the residents' socio-economic vulnerability.

Table 2: Domains of deprivation and their weight (Scottish Government, 2020)

Domain	**Weight (%)**
Income	28
Employment	28
Health	14
Education, skills and training	14
Crime	5
Housing	2

The original shapefile displays ranks for all of Scotland. However, after singling out Greater Glasgow data, not all ranks are included. Still, the ranks are in ascending and ordinal manner, providing sufficient informative value. The classification shows levels of deprivation relative to other postcode areas in Greater Glasgow.

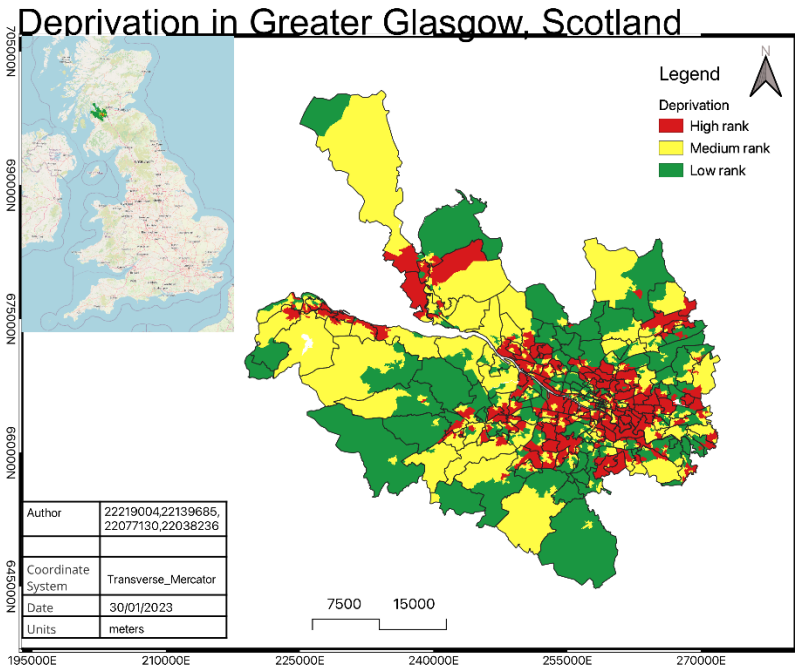

Figure 86: Map of deprivation in Greater Glasgow (the higher the rank, the higher deprivation)

Limited mobility

People that cannot evacuate are relatively more vulnerable (see e.g. Choi et al., 2019). Therefore, the layer “limited mobility” (Figure 9) classifies the share of people whose day-to-day activities are limited severely in Greater Glasgow. The shares range between 2% and 27% of which most people are of bad or very bad health. The shares for the respective postcodes were calculated manually by dividing the number of people with severely limited day-to-day activities by the sum of severely, little and no limited day-to-day activities.

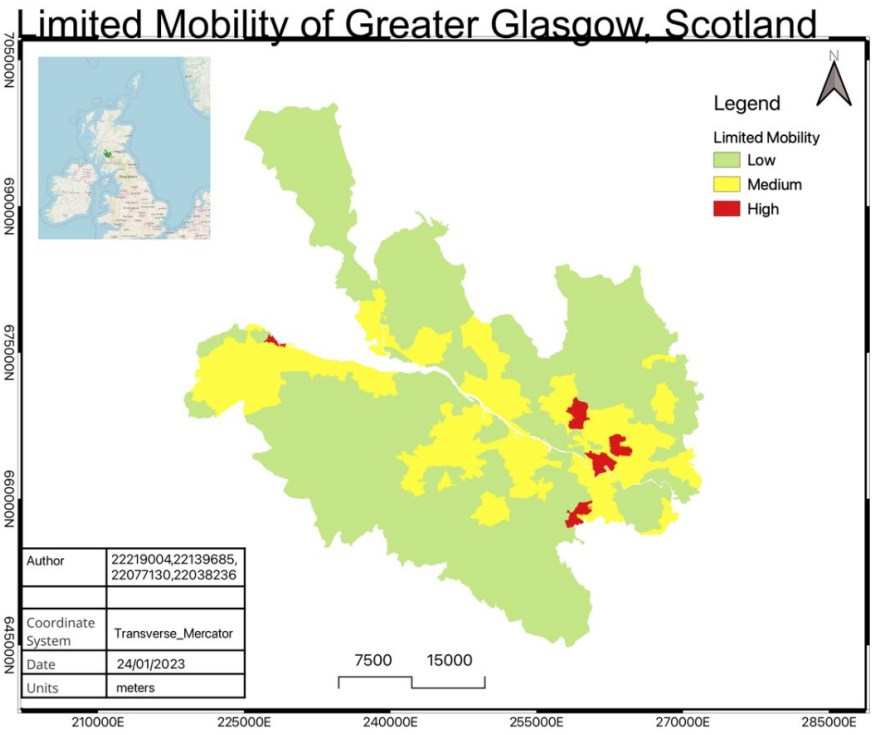

Figure 97: Map of limited mobility in Greater Glasgow

Fire stations

The last vulnerability layer is the resilience-enhancing presence of fire stations (Figure 10). Fire and rescue services' key responsibility is to save lives, and in case of flooding, they can assist with emergency services like pumping out water (National Flood Forum, n.d.) and evacuation. The classification, which is aligned with postcodes, assumes that the closer a fire station is, the shorter the response time.

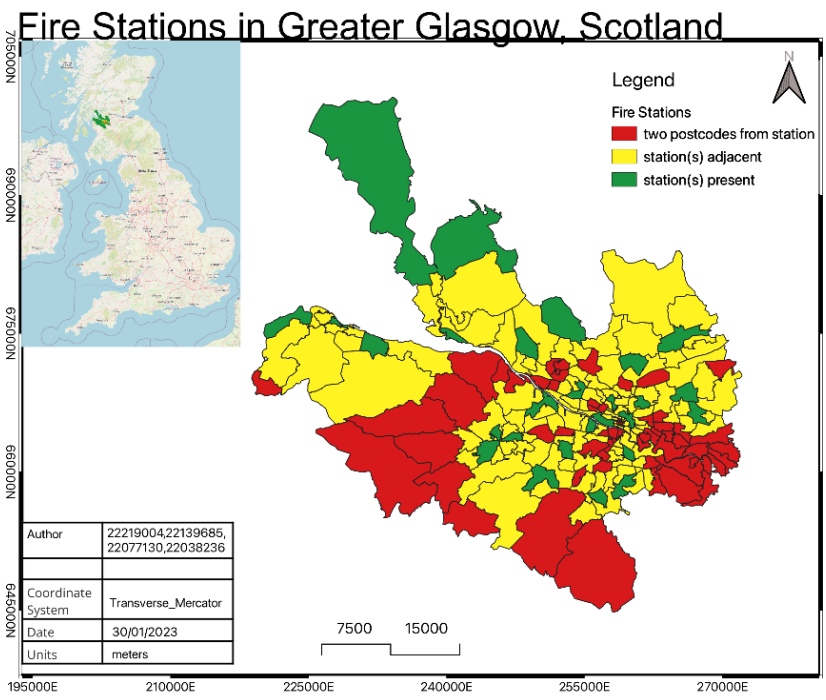

Figure 108: Map of existing fire stations in Greater Glasgow

3. Weighting Process for Risk Mapping (ArcGIS)

Each of the layers was assigned a weight, with the total summing up to 100% (Table 4). For hazard, the probable surface water flood extent was the most significant sub-layer since the subsequent analysis is conditional on this component. Since Greater Glasgow is hilly, we assigned more weight to the slope than to NDVI.

Regarding exposure, the highest weight was assigned to population density, as potential threat to human life was deemed more important over infrastructure. Being equally important components of infrastructure, road density and building density were factored in with the same weights.

Lastly, the vulnerability layer is heavily influenced by limited mobility and deprivation as these aspects aggravate individual vulnerability. The lowest weight assigned to the presence of fire stations stems from limitations to its underlying computation (see limitations).

When joining the risk modules, we applied a slightly higher weight to the hazard, because vulnerability and exposure depend on the extent to which they are impacted by the hazard.

Table 3: Weights of the risk components

	Layer	**Individual layer weight**	**Total weight**
Hazard	NDVI	0.20	0.40
	Slope	0.35	
	Surface water flood extent	0.50	
Exposure	Road density	0.30	0.30
	Building density	0.30	
	Population density	0.40	
Vulnerability	Limited mobility	0.40	0.30
	Presence of fire stations	0.20	
	Deprivation	0.40	

4. Results

The hazard of surface water flooding in Greater Glasgow is influenced by NDVI, surface flood extent and slope, which is most significant in the north and rather low in Glasgow City (Figure 11). Yet in areas with high hazard, the exposure, influenced by population, road and building density, is low (Figure 12). In general, highly populated areas have more buildings and roads and thus a higher exposure, so that only a few areas in the southeast of Greater Glasgow experience both high hazard and exposure. Since the vulnerability layers analysed are mostly linked to people, similar results to exposure can be found (Figure 13). However, the distance to fire stations in the outskirts lead to higher vulnerability levels in those areas.

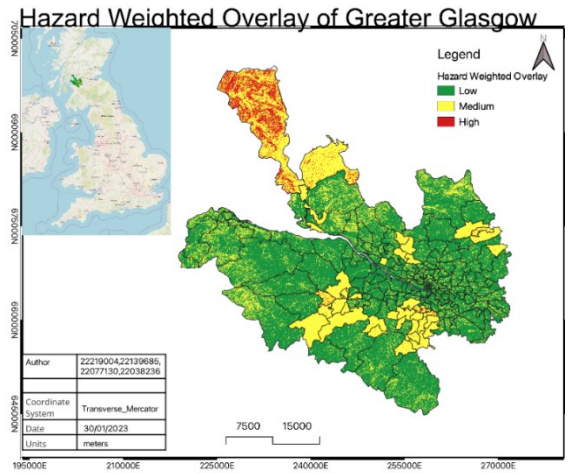

Figure 11: Weighted Overlay Map for Hazard

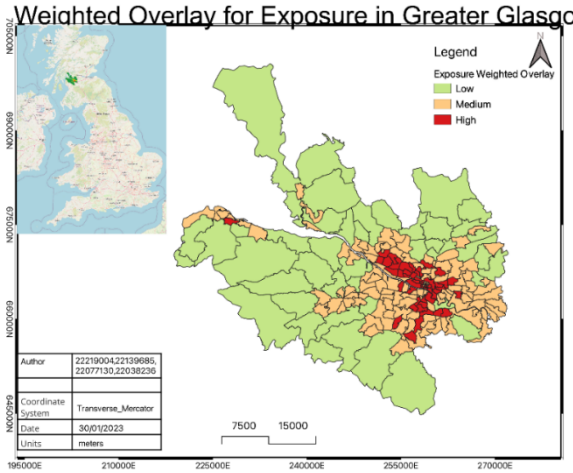

Figure 12: Weighted Overlay Map for Exposure

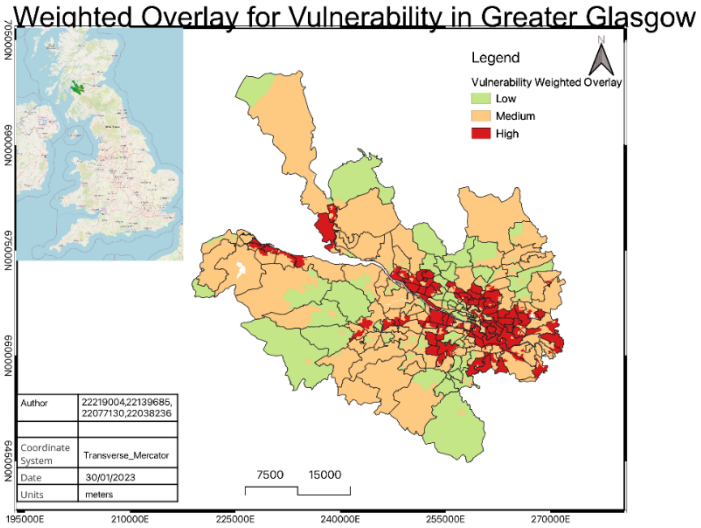

Figure 13: Weighted Overlay Map for Vulnerability

Despite the hazard being low in Glasgow City, the risk there is medium, since vulnerability and exposure are higher (Figure 14). Therefore, the highest flood risk can be found in Glasgow City. There are not many areas that experience more than one risk module being high, thus the overall flood risk is low to medium. Medium risk is also evident in the north-west corner of the region since the hazard module there is distinct. The outskirts have a rather low risk, as the impact of a potential flood is low. Only small areas in and around Glasgow city centre experience a high risk where multiple modules show distinctly high risk levels. These findings are in line with the findings of SEPA (2015), which identified Glasgow city centre and Glasgow north as Potentially Vulnerable Areas (PVAs) to flooding.

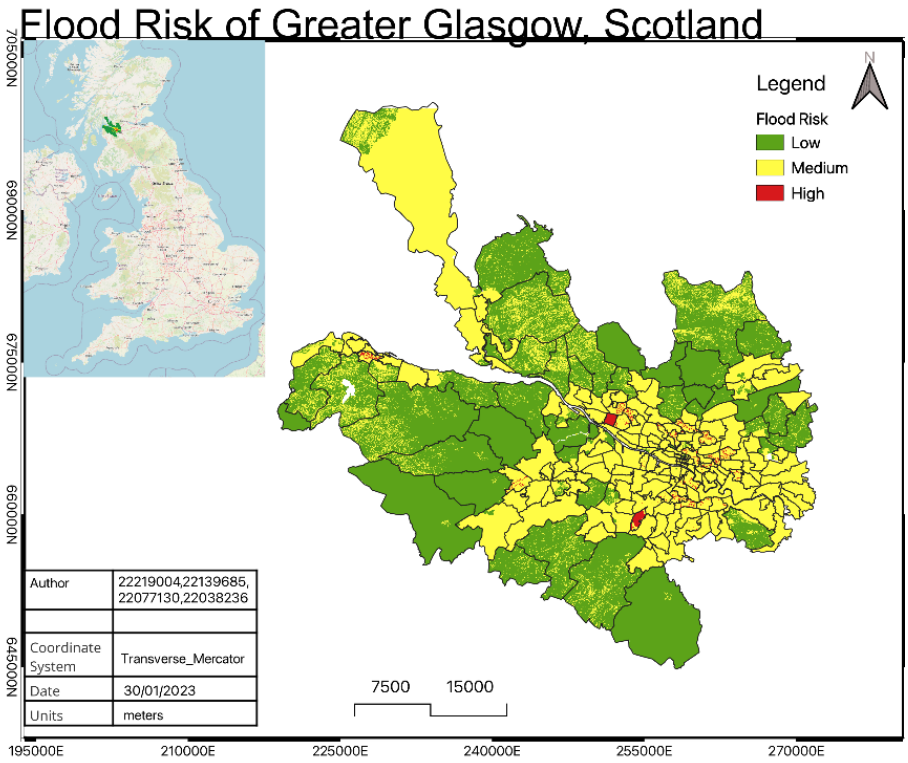

Figure 14: Flood Risk Map of Greater Glasgow

5. Discussion and Conclusion

The report analyses the flood risk in Greater Glasgow with a spatial analysis using GIS in order to be able to inform the development of targeted flood mitigation measures. These measures should target the Glasgow city area since the risk is highest there due to high levels of exposure and vulnerability.

Other variables could be investigated to develop an even more in-depth flood risk assessment. These include, but are not limited to, sewer systems, particularly as Glasgow has 'The Metropolitan Glasgow Strategic Drainage Partnership' to manage flooding (MGSDP, n.d.), different building types and critical infrastructure (e.g., hospitals, schools), age distribution, insurance penetration, and other flood sources, such as coastal and river flood accounting for climate change-related sea level rise. Additionally, in terms of methodology, there is missing data for two postcode areas in the deprivation index layer. This did, however, not alter the results significantly. The fire station layer does not take the exact locations of the fire stations into account, therefore the actual distance to the

fire station is unknown, posing a limitation as postcode areas differ in size. Once the 2022 census data is available an updated analysis could be conducted.

To conclude, even though this risk analysis for flooding has its limitations, the most influential variables for the Greater Glasgow context were chosen to determine in which areas (i.e., vulnerability and exposure module) mitigation measures can be utilised most effectively.

6. Author Contributions

All authors (Student numbers: 22139685, 22219004, 22077130, 22038236) contributed in the same amount to this report. This includes the literature reviewed, data collection, the preparation and creation of the nine layers for the three risk modules, and their analysis towards the finalised weighted overlays. Regarding the writing of the report, all parties involved contributed equally as well. As the group members helped and supported each other multiple times, more than one person, sometimes all of them, were involved in the creation of a layer.

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8. Appendices

Appendix A. Full weighted overlay table by layer.

	Layer	**Field**	**Scale**
Hazard	NDVI	0 (Waterbody)	3
		1 (Built-up area)	3
		2 (Vegetation)	2
		3 (Treecover)	1
	Slope	1 (Gentle)	1
		2 (Moderate)	2
		3 (Steep)	3
	Surface flood extent	1 (Low probability)	1
		2 (Medium probability)	2
		3 (High probability)	3
Exposure	Road density	1 (Low density)	1
		2 (Medium density)	2
		3 (High density)	3
	Building density	1 (Low density)	1
		2 (Medium density)	2
		3 (High density)	3
		1 (Low density)	1

	Population density	2 (Medium density)	2
		3 (High density)	3
Vulnerability	Presence of fire stations	1 (Two postcodes from station)	3
		2 (Station(s) adjacent)	2
		3 (Station(s) present)	1
	Deprivation	1 (High rank)	3
		2 (Medium rank)	2
		3 (Low rank)	1
	Limited mobility	1 (Low mobility)	1
		2 (Medium mobility)	2
		3 (High mobility)	3