Flood Risk Modelling using Flood Hazard & Vulnerability Factors

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Region of Interest: MMR (Mumbai Metropolitan Region), Maharashtra, India

Technologies used: QGIS

Overview

Flood risk modeling typically involves assessing two main dimensions: **flood hazard** and **flood vulnerability**. Flood hazard refers to the likelihood and intensity of flooding events based on environmental and geographic factors, while flood vulnerability considers the potential impact on human communities and infrastructure. By analyzing both dimensions, we can better understand and predict areas at greatest risk, especially within complex regions like the MMR.

To create a comprehensive model for the MMR, several factors across both hazard and vulnerability categories will be included:

- **Rainfall**: Determines the volume of water and is a key driver of flood hazard.
- **Topographic Wetness Index (TWI)**: Measures water accumulation potential and soil saturation.
- **Land Use/Land Cover (LULC)**: Impacts water absorption and runoff based on urbanization and vegetation.
- **Elevation (Digital Elevation Model - DEM)**: Influences flow paths and accumulation zones.
- **Slope**: Derived from DEM, slope affects water runoff speed and soil retention.
- **Distance from Rivers**: Proximity to water bodies increases flood exposure.
- **Drainage Density**: Reflects the network of natural and artificial drainage channels for water dispersal.
- **Infrastructure, including Roads**: Infrastructure can alter water flow paths and impact evacuation and accessibility.
- **Population and Income Factors**: Demographic data can provide insights into vulnerability, especially in densely populated or economically disadvantaged areas.

Region of Interest

The Mumbai Metropolitan Region (MMR) was selected for flood risk modeling due to its unique combination of geographical, topological, and socioeconomic factors that significantly contribute to flooding.

- **Geographical Significance**: MMR is a coastal region directly influenced by the Arabian Sea, making it susceptible to storm surges and heavy rainfall, particularly during the monsoon season. The presence of major water bodies and rivers further exacerbates the flooding risk

- **Topological Vulnerability**: The region features a mix of low-lying coastal areas and hilly terrains, which complicate drainage and water absorption. Dense urban development and inadequate drainage infrastructure in many areas increase the likelihood of severe flooding
- **Socioeconomic Context**: With a high population density and a significant number of informal settlements, MMR faces unique challenges related to flood preparedness and response. Economic activities concentrated in flood-prone zones heighten the potential for disruption during flood events
- **Historical Context**: The region has experienced devastating floods in the past, highlighting the urgent need for effective flood risk management strategies and better understanding of flood dynamics

Rainfall

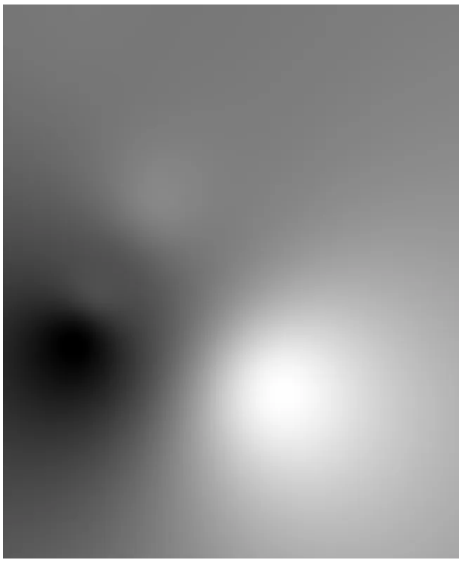
The MMR region consists of 5 districts:

- Raigad (Partial)
- Palghar (Partial)
- Thane
- Mumbai Suburban
- Mumbai City

After collecting the average annual rainfall data for these districts from https://chrsdata.eng.uci.edu/, I formatted and downloaded the data as a .csv file to be used in QGIS later.

On QGIS, I uploaded the shapefile for the MMR Region. I included the datapoints by adding a `Delimited Text Layer` on top of the shapefile.

Now, from the `Interpolation Toolbox`, I chose `IDW Interpolation` to add a Vector Layer for the interpolated data. For a more accurate and less pixelated layer, I chose a pixel size of **0.001** and a distance coefficient P of **2.0**. I ran the algorithm resulting in an **interpolated vector layer.**



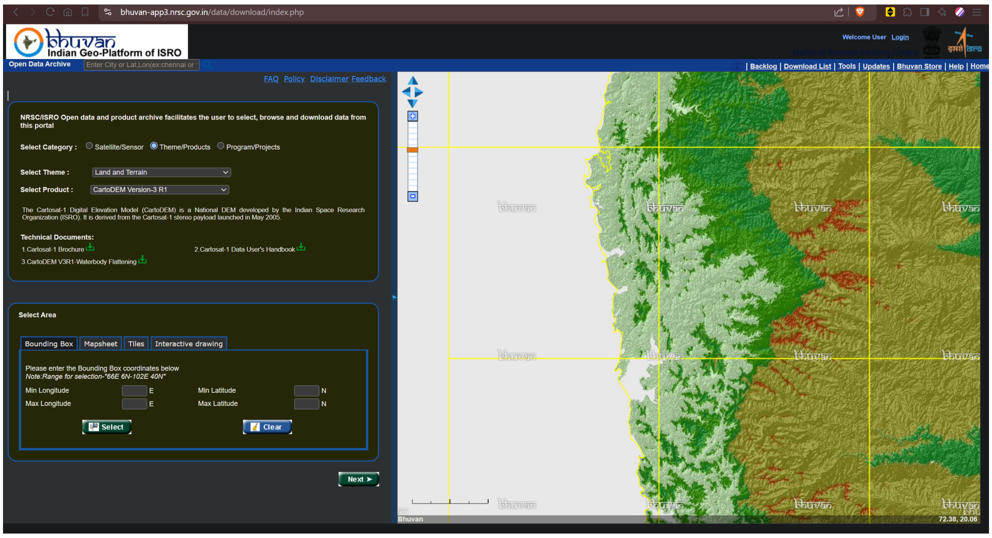
I moved the shapefile on top of the **vector layer** which revealed the extra space.

To remove this, I went to the `Raster Tool` and chose `Extraction > Clip Raster by Mask Layer` to extract only the shapefile. I used the **Interpolated Layer** as the input layer and the S**hapefile** as the mask layer. This resulted in a crisp extraction of the interpolation. To model the intensity of rainfall as a blue scale, I double-clicked the newly extracted `Clipping>Properties` and changed the `Render Type` to **Singleband Pseudocolor** and chose **Blues** as the `Color Ramp` .

Dark blue near the coastal area (Mumbai City) is justified due to low coastal areas.

Elevation

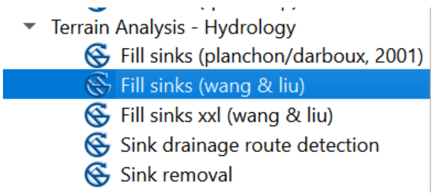
The most straight-forward of all, just imported data from: https://bhuvan-app3.nrsc.gov.in/data/download/index.php

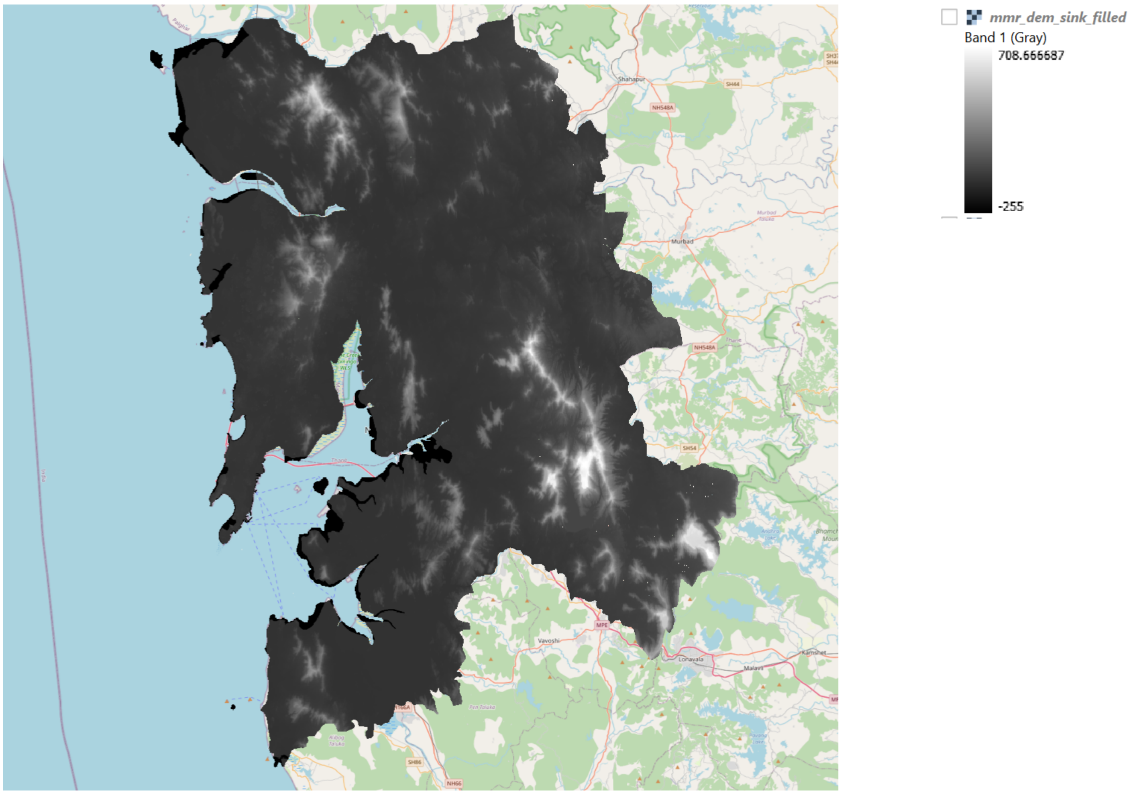


From CartoDEM3 we take 4 tiles which are required to cover our ROI and then merge them in QGIS to get one raster layer.

We then fill the sinks in it using `Fill sinks (wang & liu)`

This gets rid of sudden changes in the DEM data which would have resulted in absurd slopes and would have thus hindered further analysis.

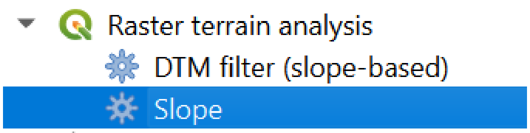




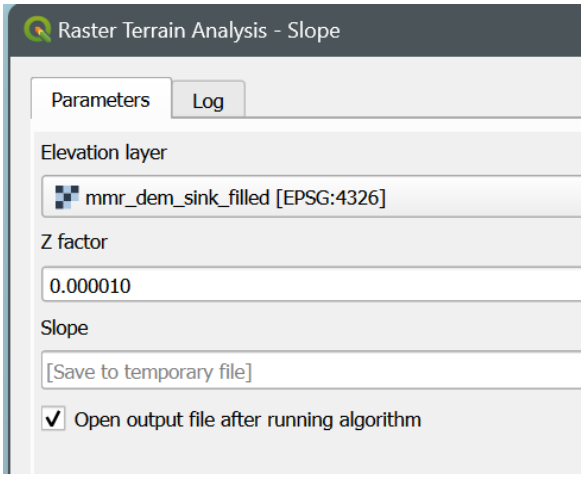
Sink-filled DEM

Slope

From the sink-filled DEM we get the slope map using the `Slope` tool in the `Raster terrain analysis` toolbox.



The z-factor is a conversion factor that adjusts the units of measure for the vertical (or elevation) units when they are different from the horizontal coordinate (x,y) units of the input surface. It is the number of ground x,y units in one surface z-unit. If the vertical units are not corrected to the horizontal units, the results of surface tools will not be correct.

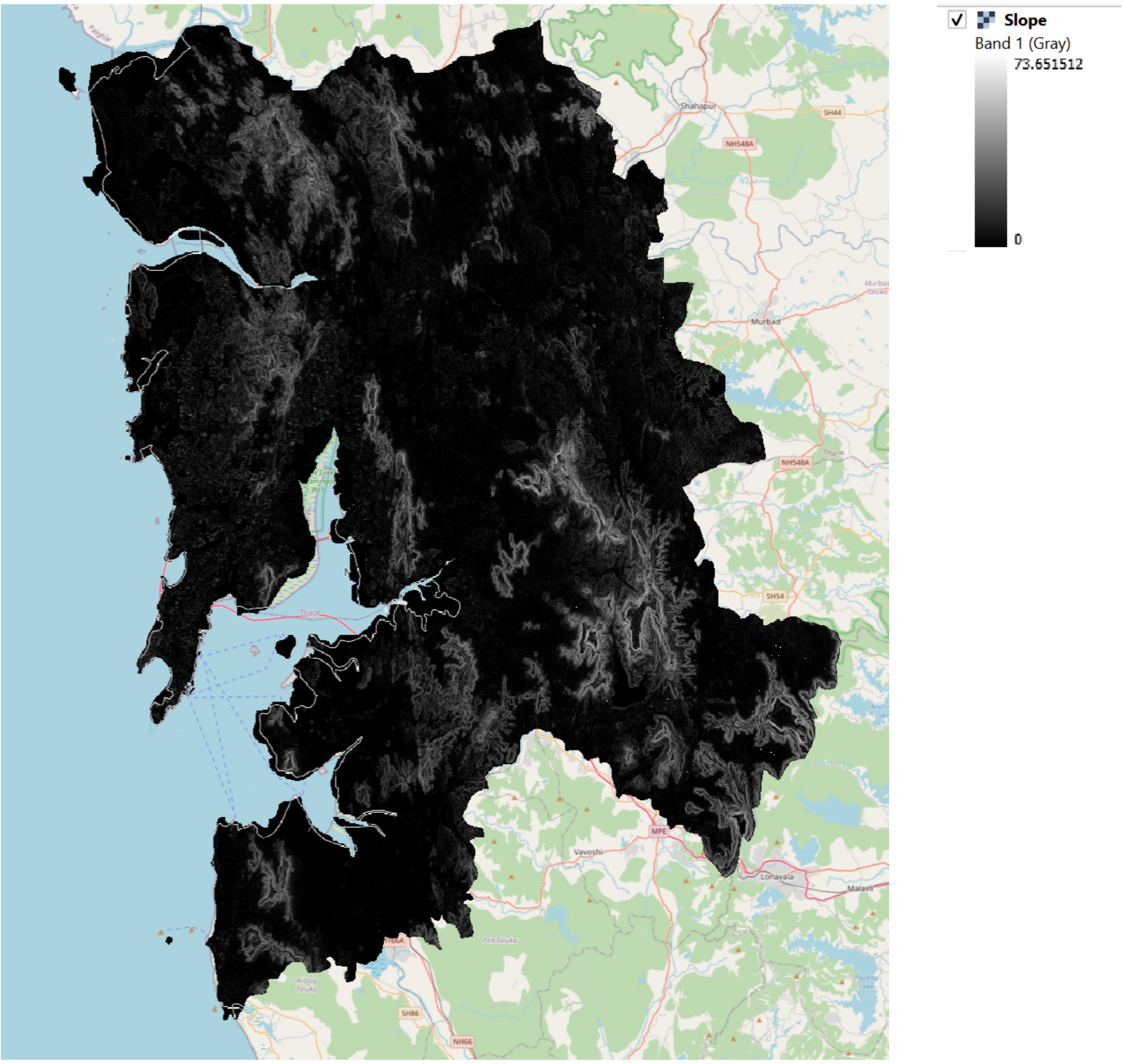


Given that the latitude of Mumbai is about 19°, we choose our Z-factor to be 0.00000956.

Source: https://pro.arcgis.com/en/pro-app/latest/tool-reference/spatial-analyst/applying-a-z-factor.htm

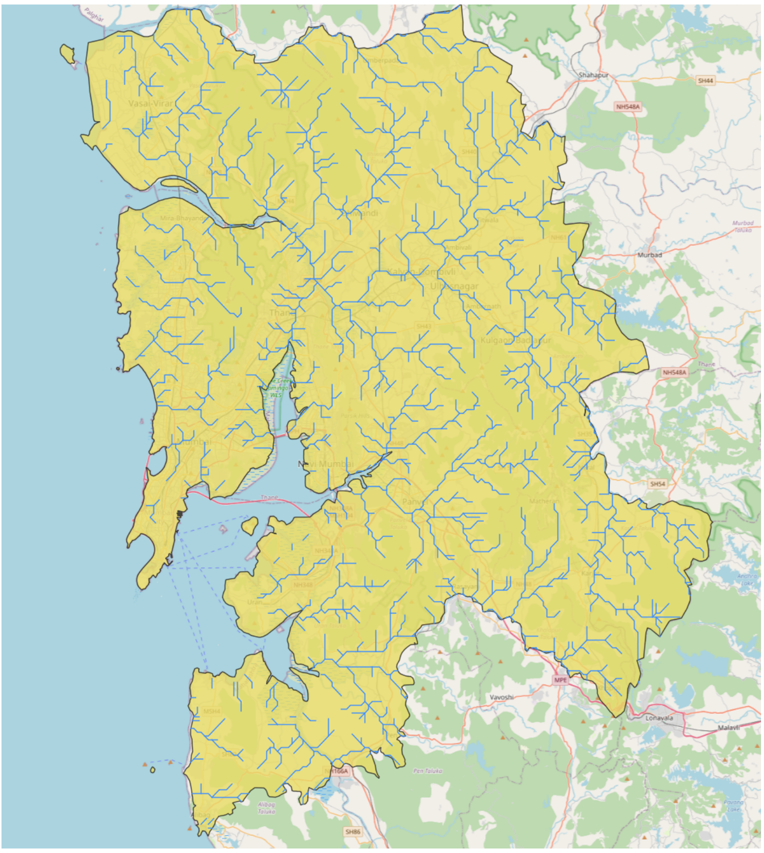
If your x,y units are decimal degrees and your z-units are meters, some appropriate z-factors for particular latitudes are as follows:

Latitude	Z-factor
0	0.00000898
10	0.00000912
20	0.00000956
30	0.00001036
40	0.00001171
50	0.00001395
60	0.00001792
70	0.00002619
80	0.00005156



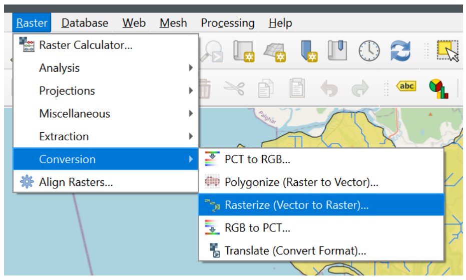
Slope raster with z-factor 0.00000956

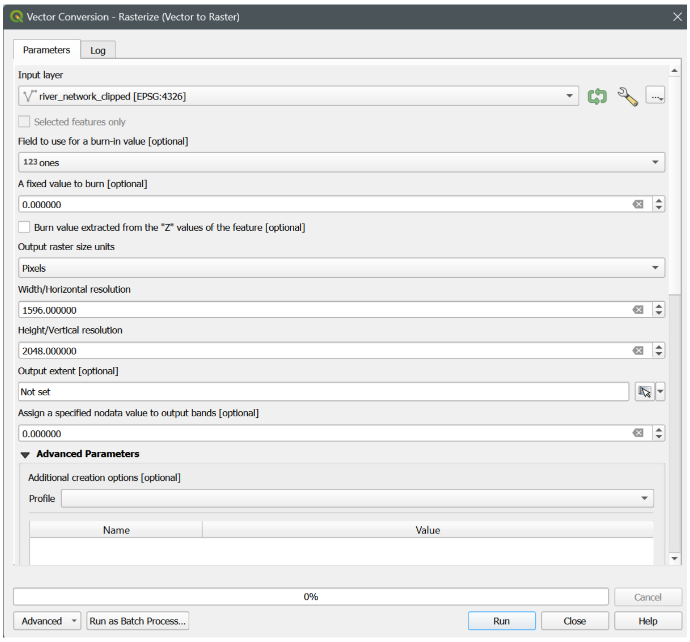
Drainage Density

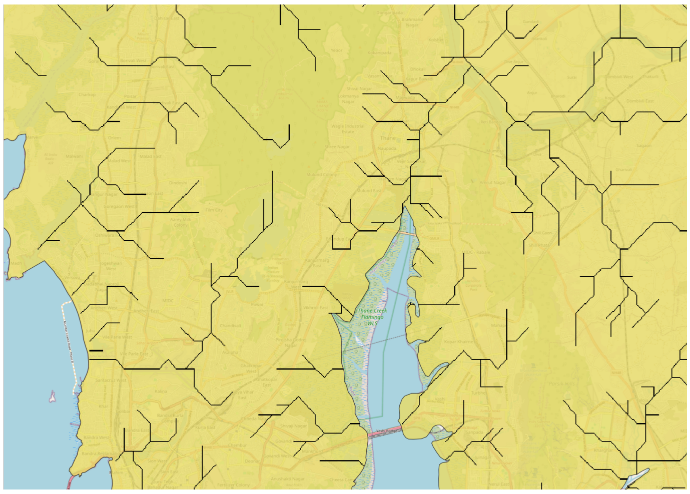


River network vector clipped to ROI

We create a Raster layer out of the river network vector, by adding an all ones field in the attributes table of the river network vector and then going to `Raster → Conversion → Rasterize` and select the `ones` field to burn in values. We also choose an appropriate resolution.







Now from the `Interpolation` toolbox we use the `Line density` tool to create a Raster layer for drainage density.

In QGIS, the **Line Density Interpolation** tool calculates the density of line features within a specified area and distributes this density across a raster. It's often used for things like estimating road or stream density. Here's what the key parameters mean:

1. Search Radius

- **Search Radius** defines the distance (in map units) around each cell where QGIS will search for line features to include in the density calculation.
- A smaller radius captures density in a more localized way, focusing on nearby lines, while a larger radius gives a broader, more generalized density view.
- For a river stream network, the search radius should ideally relate to the extent of typical watershed sizes or spacing between major tributaries in your study area.
    - **Suggested Value**: Start with a radius around 500–1000 meters for a city drainage network. However, you may need to adjust this based on the specific width and spacing of the river

network.

2. Pixel Size

- **Pixel Size** is the resolution of the output raster layer. Smaller pixel sizes give higher resolution but can increase processing time and file size.
- The choice of pixel size depends on your desired level of detail. For a city-scale analysis, a pixel size of around 10–30 meters might be suitable, providing a good balance between detail and performance.
  - **Suggested Value**: 10–30 meters is typical for a city stream network. Lower values like 5 meters can be used for finer resolution, but only if needed for high precision.

Now because we are dealing with degrees in the tool, instead of meters, we do the following conversion (considering 19 degrees latitude):

1. Search Radius in Degrees

For a target search radius of 500–1000 meters:

- **Latitude**: 500 meters ≈ 0.0045 degrees, 1000 meters ≈ 0.009 degrees (this is nearly constant along latitude).
- **Longitude**: Convert using `distance in degrees ≈ (distance in meters / 111,320) / cos(19°)`.
- For 500 meters ≈ 0.0047 degrees
- For 1000 meters ≈ 0.0094 degrees

2. Pixel Size in Degrees

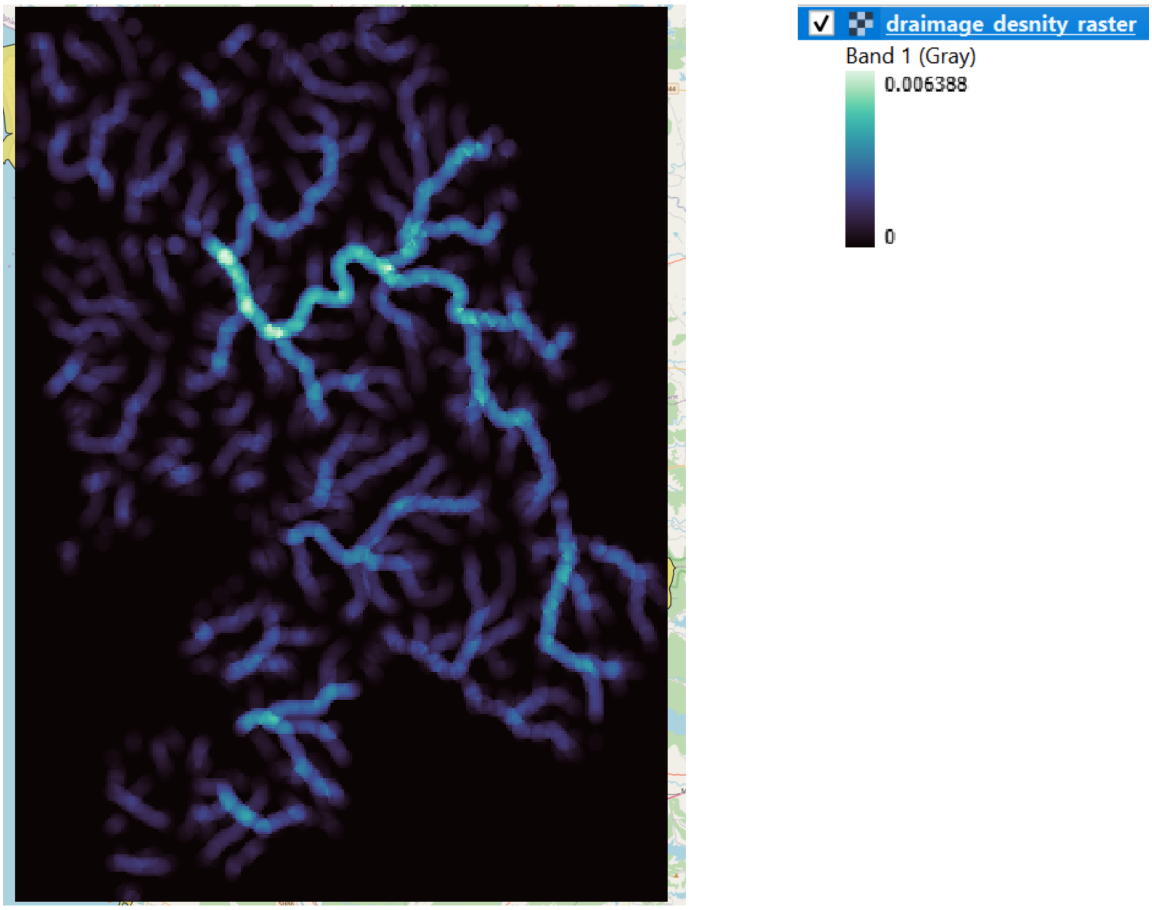
For a pixel size of around 10–30 meters:

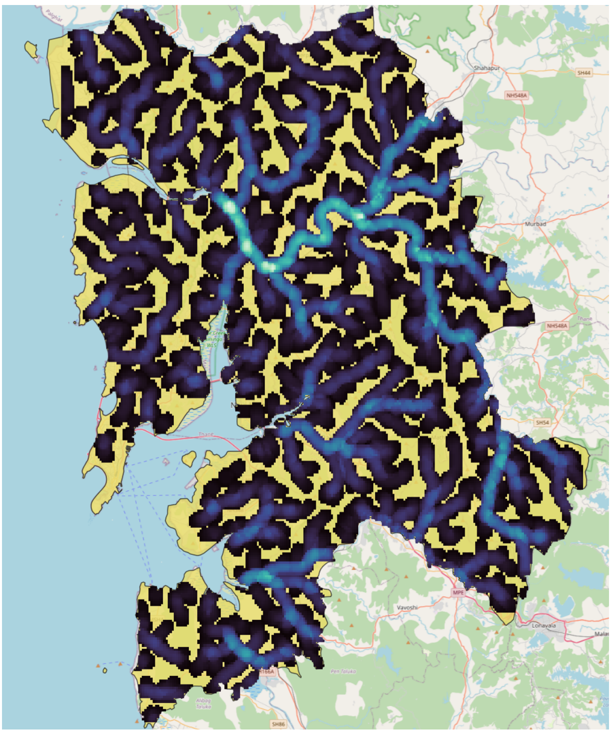
- **Latitude**: 10 meters ≈ 0.00009 degrees, 30 meters ≈ 0.00027 degrees.
- **Longitude**: Convert similarly based on 19° latitude.
- For 10 meters ≈ 0.00009 degrees
- For 30 meters ≈ 0.00028 degrees

Approximate Values for 19° Latitude

- **Search Radius**: ~0.0047–0.0094 degrees
- **Pixel Size**: ~0.00009–0.00028 degrees

For Search radius 1000m = 0.0094 and Pixel size of 300m = 0.0028 degrees:

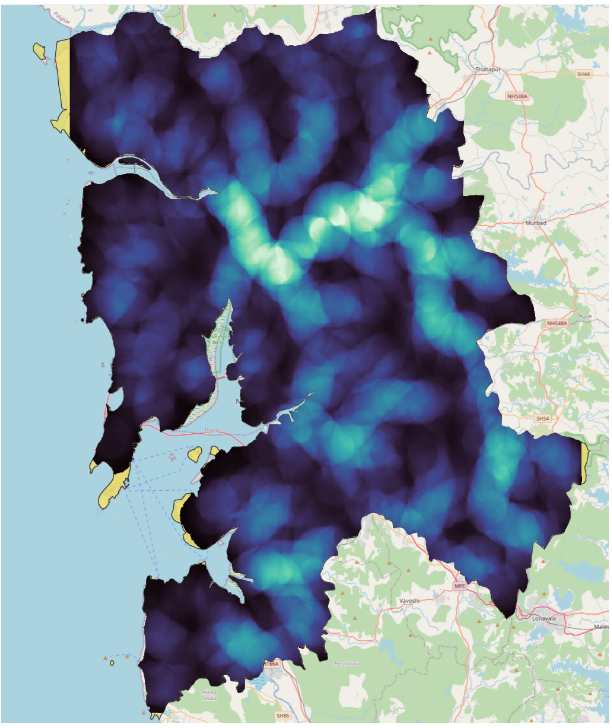




after clipping by mask layer

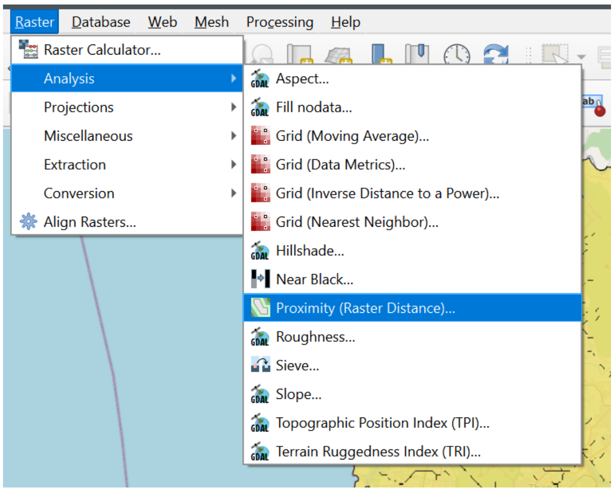
So here we see that there are many no-data values, which is bad because these areas will then have misleading calculations. Therefore we need to increase the search radius. We triple the radius to 3000m:

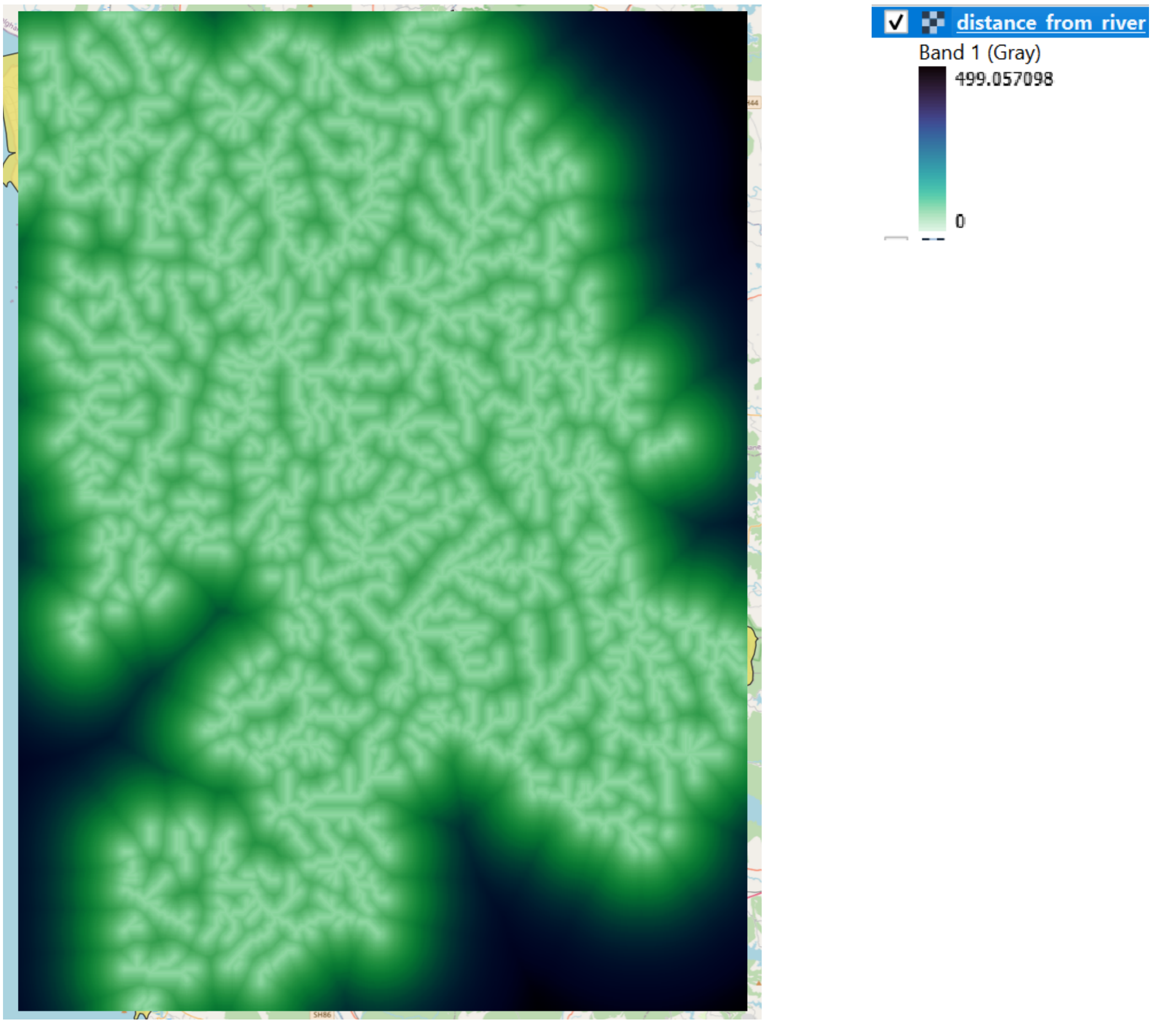
For Search radius 3000m = 0.0282 and Pixel size of 100m = 0.0009 degrees:

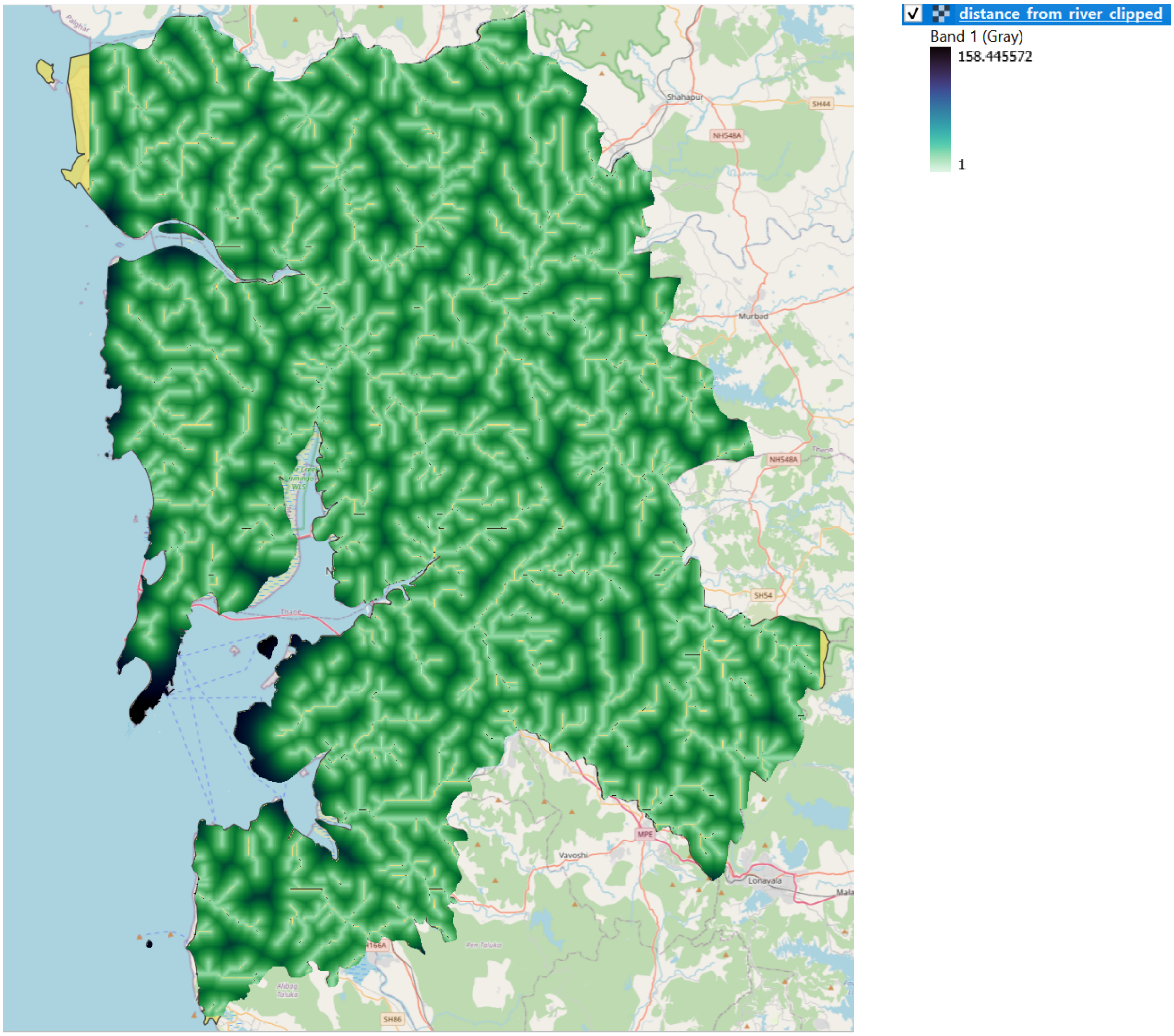


Beauty. Now there are no random “holes” in our drainage density layer.

Distance from River



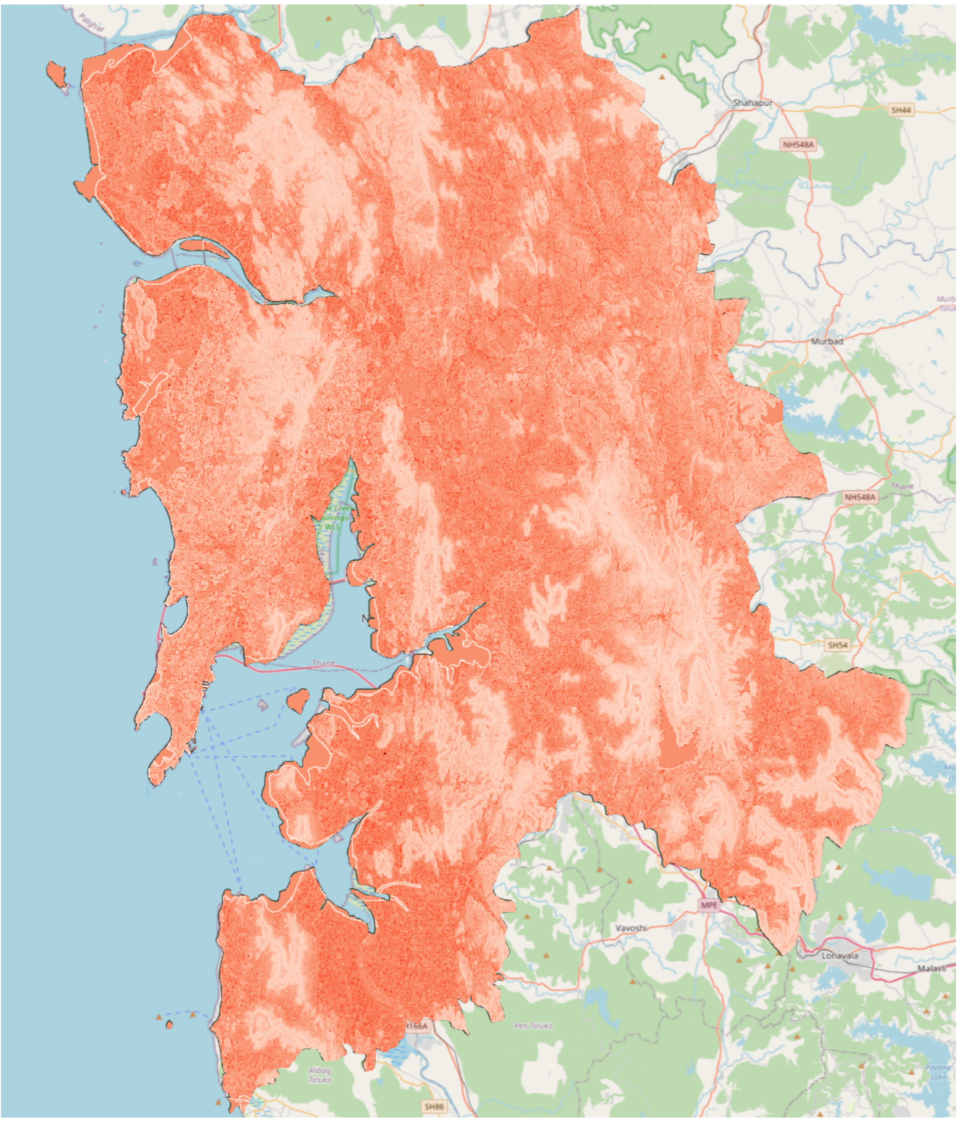

distance from river
Band 1 (Gray)
499.057098
0

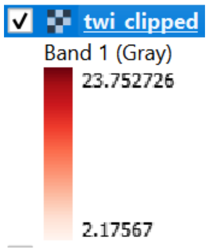


plotted with gamma = 0.24 for clarity

TWI (Topological Wetness Index)

```
ln (("contributing_area@1"+1*30) / tan("radient@1"))
```





Flood risk modeling

So finally we have 7 factors which will determine our flood risk. These are:

1. Slope
2. Elevation
3. Rainfall
4. LULC
5. TWI
6. Distance from rivers
7. Drainage density

Weighing factors through literature and AHP

Our final flood risk model works on a weighted average of the 7 layers listed above. To decide these weights we did an extensive literature review. Some did cost/economic damage based analysis to decide on the weights (https://www.sciencedirect.com/science/article/abs/pii/S2212420918314493?via%3Dihub). Others create a frequency ratio map (https://link.springer.com/article/10.1007/s13201-018-0710-1). However, one approach that strikes best to us is an ANN based analysis performed by Tamiru *Et al*. (https://onlinelibrary.wiley.com/doi/10.1155/2021/6128609), in this study, ground-truthing points collected from the historical flood events of 2006 were used as targeting data during the training. A rough flood hazard map generated in feedforward was compared with the actual data, and the errors were propagated back into the NN with the backpropagation technique, and this step was repeated until a good agreement was made between the result of the GIS-ANN and the historical flood events. The results were overlapped with ground-truthing points at 88.46% and 89.15% agreement during training and validation periods.

This results in importance scores for various factors affected flood as shown below.

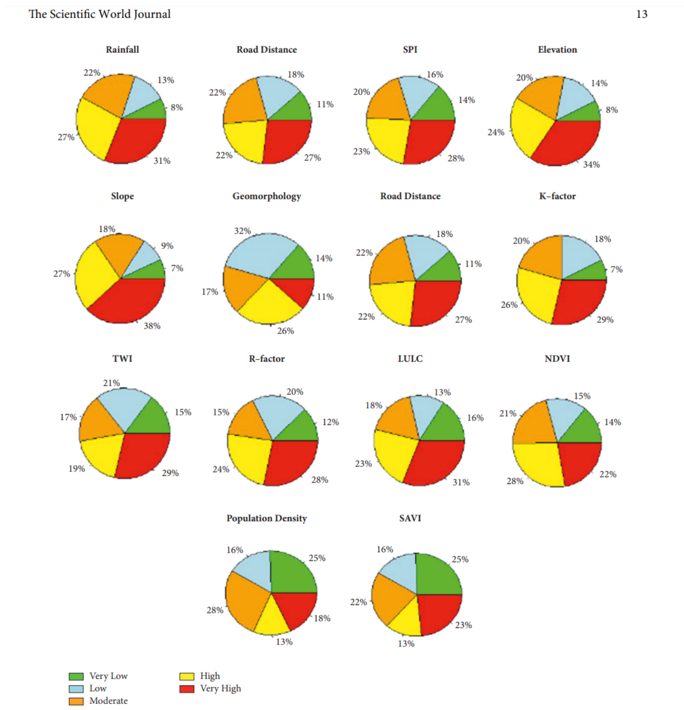


Figure 10: The percentage of importance of flood causing factors.

We consider these scores (discarding the ones we aren't considering and scaling others accordingly) along with drainage density and distance from river.

Now, based on these we perform an Analytical Hierarchy Process (AHP). It is a method to support multi-criteria decision making, and was originally developed by Prof. Thomas L. Saaty (https://ijahp.org/index.php/IJAHP/article/view/590). AHP derives ratio scales from paired comparisons of criteria, and allows for some small inconsistencies in judgments. Inputs can be actual measurements, but also subjective opinions. As a result, priorities (weightings) and a consistency ratio will be calculated. Internationally AHP is used in a wide range of applications, for example for the evaluation of suppliers, in project management, in the hiring process or the evaluation of company performance.

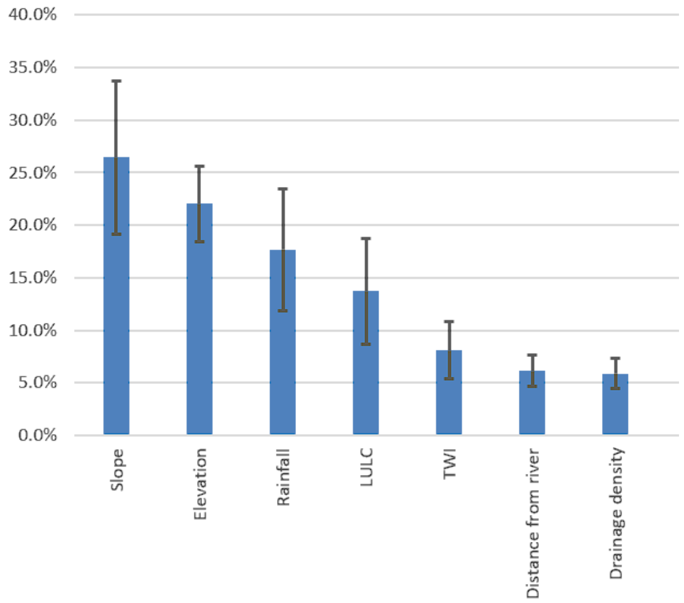
Mathematically the method is based on the solution of an Eigenvalue problem. The results of the pair-wise comparisons are arranged in a matrix. The first (dominant) normalized right Eigen vector of the matrix gives the ratio scale (weighting), the Eigenvalue determines the consistency ratio.

i	j	Criteria A	B	more important ? A or B	Scale (1-9)
1	2	Slope	Elevation	A	1
1	3		Rainfall	A	1
1	4		LULC	A	3
1	5		TWI	A	3
1	6		Distance from river	A	5
1	7		Drainage density	A	5
1	8			A	3
2	3	Elevation	Rainfall	A	1
2	4		LULC	A	2
2	5		TWI	A	3
2	6		Distance from river	A	3
2	7		Drainage density	A	4
2	8			A	3
3	4	Rainfall	LULC	A	1
3	5		TWI	A	3
3	6		Distance from river	A	2
3	7		Drainage density	A	2
3	8			A	1
4	5	LULC	TWI	A	3
4	6		Distance from river	A	2
4	7		Drainage density	A	2
4	8			A	3
5	6	TWI	Distance from river	A	2
5	7		Drainage density	A	2
5	8			A	3
6	7	Distance from river	Drainage density	A	1
6	8			A	1
7	8			A	3

These are the weights we obtain:

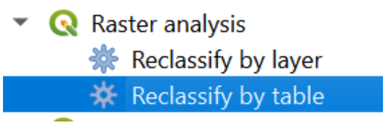
Table	Criterion	Comment	Weights	+/-
1	Slope	Slope derived from DEM	26.4%	7.3%
2	Elevation	Direct projection of DEM	22.0%	3.6%
3	Rainfall	Rainfall data over ROI	17.7%	5.8%
4	LULC	Land Use Land Cover	13.7%	5.0%
5	TWI	Topological Wetness Index	8.1%	2.7%
6	Distance from river	Derived from river network raster	6.1%	1.5%
7	Drainage density	Line density extrapolation of river network	5.9%	1.4%

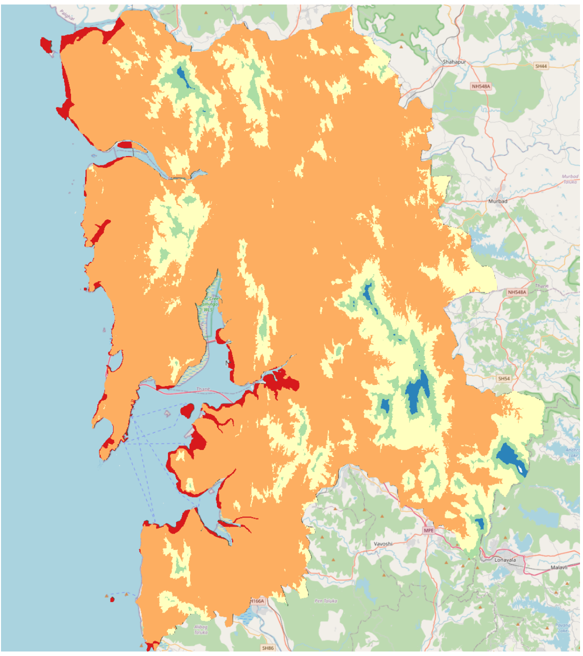
Matrix		Slope 1	Elevation 2	Rainfall 3	LULC 4	TWI 5	Distance for river 6	Drainage density 7	0 8	0 9	0 10	normalized principal Eigenvector
Slope	1	1	1	1	3	3	5	5	-	-	-	26.44%
Elevation	2	1	1	1	2	3	3	4	-	-	-	22.05%
Rainfall	3	1	1	1	1	3	2	2	-	-	-	17.69%
LULC	4	1/3	1/2	1	1	3	2	2	-	-	-	13.73%
TWI	5	1/3	1/3	1/3	1/3	1	2	2	-	-	-	8.10%
Distance from river	6	1/5	1/3	1/2	1/2	1/2	1	1	-	-	-	6.12%
Drainage density	7	1/5	1/4	1/2	1/2	1/2	1	1	-	-	-	5.87%
0	8	-	-	-	-	-	-	-	1	-	-	0.00%
0	9	-	-	-	-	-	-	-	-	1	-	0.00%
0	10	-	-	-	-	-	-	-	-	-	1	0.00%



S. no.	Factor	% importance	Normalized weights
1	Slope	26.44	0.2644
2	Elevation	22.05	0.2205
3	Rainfall	17.69	0.1769
4	LULC	13.73	0.1373
5	TWI	8.10	0.0810
6	Distance from river	6.12	0.0612
7	Drainage density	5.87	0.0587

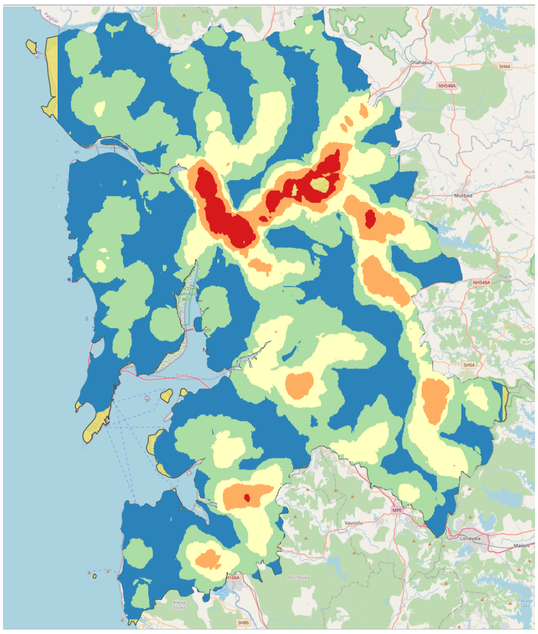
Reclassifying layers in QGIS



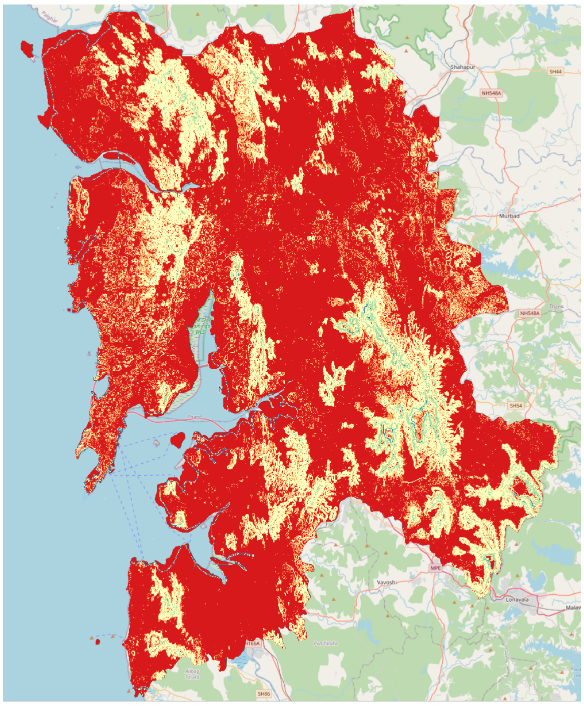


Reclassified Elevation

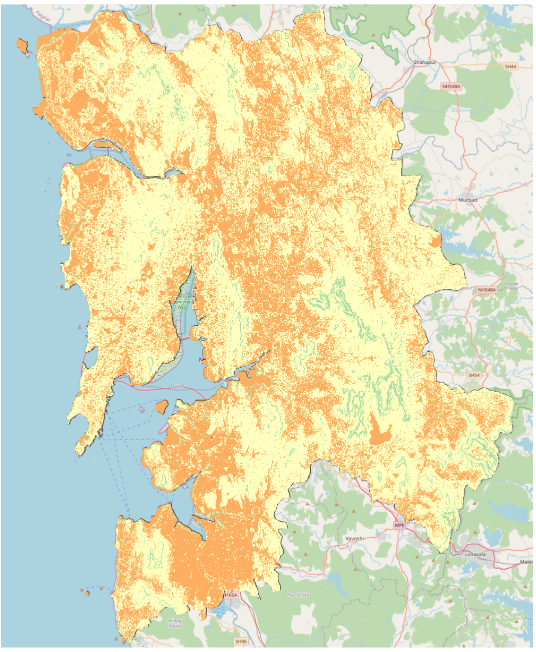
Reclassified distance from river



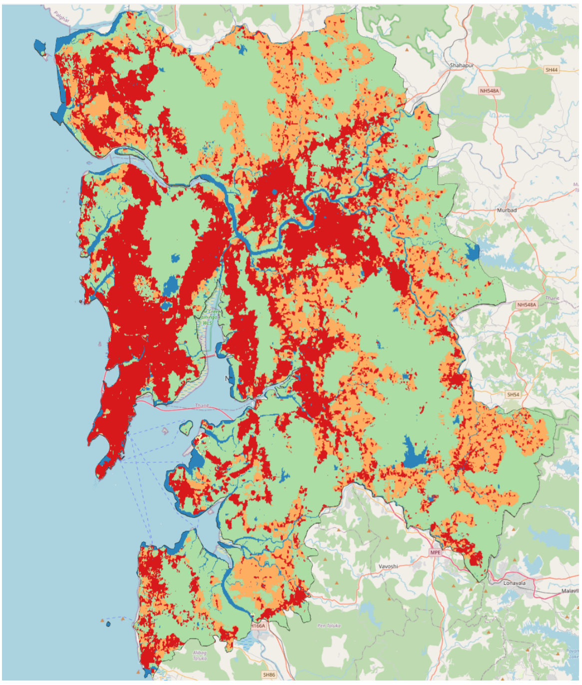
Reclassified drainage density



Reclassified by slope



Reclassified TWI



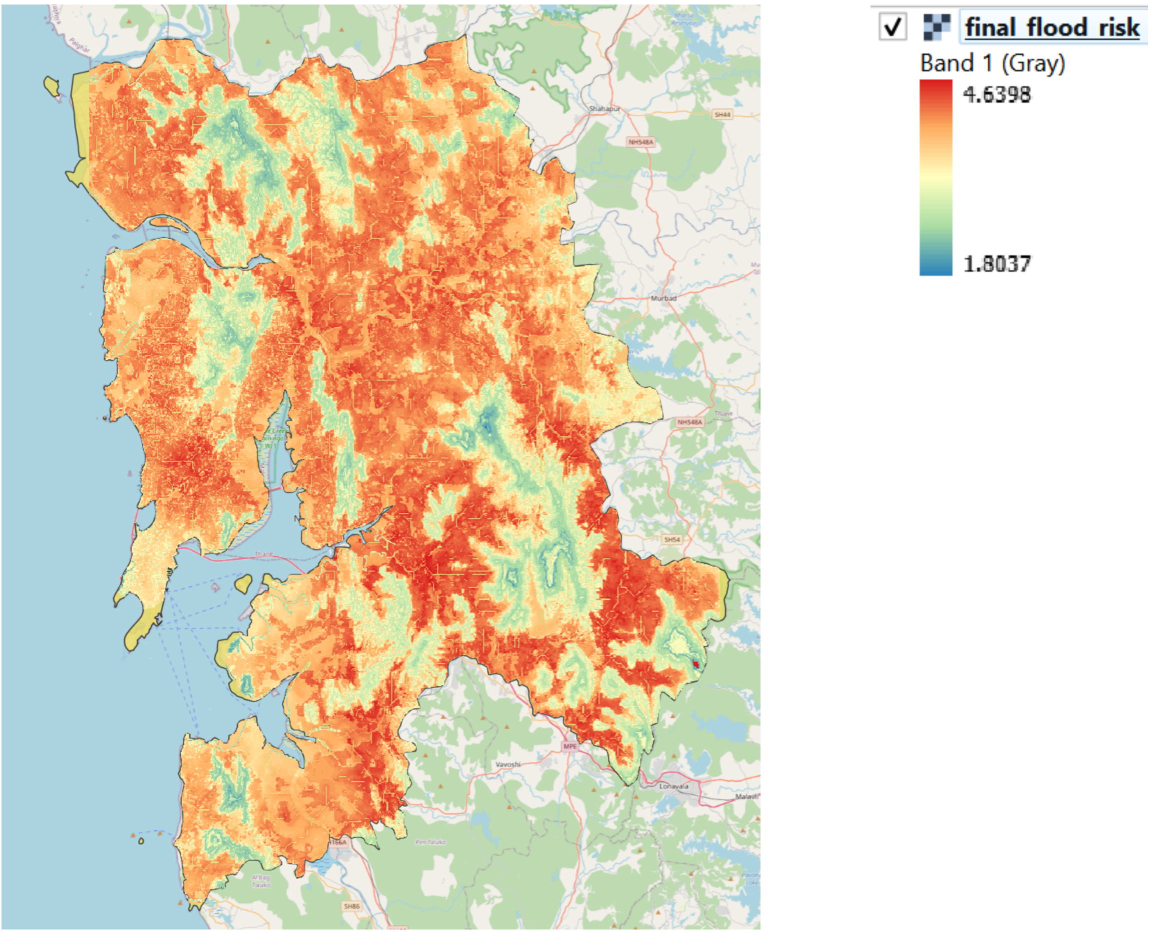
Reclassified LULC

Final Raster Calculation

After getting all these reclassified layers, we simply use the raster calculator to get our final flood risk map. Note that we took a gaussian filtered version of the rainfall reclassified layer to get a smoother output.

Formula used:

```
(0.2644*"slope@1") + (0.2205*"elevation@1") + (0.1769*"rainfall_gaussian_filtered@1") + (0.1373*"lulc@1") +
(0.0810*"twi@1") + (0.0612*"dist_riv@1") + (0.0587*"drain_dens@1")
```



Final risk map

Flood Risk Factors in MMR Districts: Topology, Geography, Socioeconomic Factors

1. Mumbai City District

- **Flood Risk**: **Highest**
- **Topological Factors**:
  - **Low Elevation**: Mumbai City is primarily low-lying, with an average elevation of just 14 meters above sea level. This positioning makes it particularly susceptible to flooding during heavy rainfall and high tides.
  - **Coastal Location**: As a coastal city, Mumbai is directly exposed to the Arabian Sea, which increases the risk of coastal flooding and storm surges during monsoon season and cyclones.
  - **Dense Water Networks**: The presence of numerous rivers, creeks, and backwaters (notably the Mithi River) within the city significantly increases flood potential, especially during periods of heavy rainfall.
  - **Flat Terrain**: The predominantly flat topography allows water to accumulate rather than drain away, exacerbating flooding conditions.

- **Urban Density**: High population density leads to extensive urban development, which often reduces the land's natural ability to absorb water and increases surface runoff.
- **Geographical Factors**:
  - **Influence of the Western Ghats**: The proximity to the Western Ghats contributes to orographic rainfall, which can lead to intense precipitation events in the city.
  - **Urban Geography**: The densely built environment, characterized by high-rise buildings and limited green spaces, reduces natural drainage and water absorption.
  - **Inadequate Drainage Infrastructure**: Despite extensive drainage systems, many areas suffer from flooding due to inadequate capacity to handle extreme rainfall, especially during high tides.
- **Socioeconomic Factors**:
  - **High Population Density**: Mumbai has one of the highest population densities in the world, particularly in informal settlements, which increases vulnerability to flooding.
  - **Economic Significance**: As a major financial and commercial hub, the city faces significant economic disruption during floods, affecting businesses and livelihoods.
  - **Limited Infrastructure**: Many low-income communities lack adequate flood defenses and resources for disaster preparedness, exacerbating the impacts of flooding on vulnerable populations.
  - **Social Inequities**: The urban poor, residing in flood-prone areas, often face greater risks and have limited access to emergency services and recovery resources.

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2. Raigad District

- **Flood Risk**: **Moderate to High**
- **Topological Factors**:
  - **Varied Elevation**: Raigad features a mix of coastal plains and hilly terrains. While coastal areas are low-lying and vulnerable to flooding, the hilly regions provide some natural protection.
  - **Extensive River Networks**: The presence of major rivers, such as the Kundalika and Pavana, increases the risk of riverine floods, particularly in agricultural areas during heavy monsoon rains.
  - **Natural Drainage**: Hilly terrains aid in natural drainage, but urbanization in low-lying areas can impede runoff, leading to flooding.
- **Geographical Factors**:
  - **Proximity to the Arabian Sea**: Coastal areas in Raigad face risks from storm surges and tidal flooding, although generally less intense than in Mumbai.
  - **Forest Cover**: The significant forested regions in the Western Ghats contribute to water absorption and can help mitigate flood risks in some areas.
  - **Land Use Patterns**: Increasing urbanization in low-lying areas poses risks, as developing infrastructure often lacks adequate drainage systems.
- **Socioeconomic Factors**:

- **Economic Dependency on Agriculture**: Many communities rely on agriculture, making them vulnerable to crop loss during flooding.
- **Informal Settlements**: The presence of informal settlements in flood-prone areas increases vulnerability due to limited access to resources and infrastructure.
- **Emergency Services**: Rural areas often lack adequate emergency services, delaying response times during flood events.

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3. Palghar District

- **Flood Risk**: **Moderate**
- **Topological Factors**:
  - **Mixed Terrain**: Palghar features coastal lowlands and hilly inland areas. While coastal regions are more susceptible to flooding, the hills help manage water runoff.
  - **Presence of Rivers**: The Palghar River and other local water bodies contribute to flood risks, particularly during heavy monsoon rains.
  - **Soil Composition**: Alluvial soils in flood-prone areas retain water, leading to prolonged flooding.
- **Geographical Factors**:
  - **Coastal Exposure**: The district's coastline faces potential storm surges and high tides, although impacts are generally less severe than in Mumbai City.
  - **Natural Barriers**: Portions of the Western Ghats act as barriers to intense rainfall, reducing flood severity in some regions.
  - **Land Use Patterns**: While much of Palghar is rural, rapid urbanization in certain areas raises flood risk due to inadequate drainage and planning.
- **Socioeconomic Factors**:
  - **Rural Economy**: The economy is predominantly agricultural, meaning floods can disrupt livelihoods but impact smaller populations than in urban areas.
  - **Indigenous Communities**: Vulnerable groups often lack the resources and infrastructure needed for flood preparedness and recovery.
  - **Emerging Urban Areas**: Rapid development in certain regions increases flood risk for new settlements that may not be equipped with adequate drainage systems.

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4. Thane District

- **Flood Risk**: **High**
- **Topological Factors**:
  - **Low-Lying Coastal Areas**: Thane includes extensive low-lying regions along the coast and around lakes and rivers, making these areas particularly susceptible to flooding.
  - **Numerous Water Bodies**: The presence of lakes (e.g., Upvan Lake) and rivers (such as the Ulhas River) increases the potential for overflow during heavy rainfall events.
  - **Flat Terrain**: Similar to Mumbai, Thane's flat topography facilitates water accumulation, prolonging flood conditions.

- **Geographical Factors**:
  - **Western Ghats Influence**: The proximity to the Western Ghats enhances rainfall intensity during the monsoon season due to orographic effects.
  - **Rapid Urban Expansion**: The rapid growth of urban areas in flood-prone regions raises vulnerability due to increased impervious surfaces and strained drainage systems.
  - **Drainage Infrastructure**: While Thane has a relatively better drainage system compared to rural areas, it still faces challenges during extreme weather events.
- **Socioeconomic Factors**:
  - **Population Growth**: High population density from rapid urbanization leads to increased flood vulnerability in low-lying areas.
  - **Economic Diversification**: The district has diverse economic activities, and flooding can disrupt both commercial and residential sectors, impacting daily wage earners.
  - **Inequitable Resource Access**: Low-income communities in flood-prone zones often lack adequate infrastructure and emergency services, increasing their vulnerability during flood events.

References

- Rainfall data: https://www.mahahp.gov.in/DisplayRainfall.aspx?data=Rainfall
- Shapefiles: https://github.com/IDFCInstitute/Cities_data/tree/master/Mumbai/Shapefiles/Municipal_Boundary
- LULC: https://livingatlas.arcgis.com/landcoverexplorer/
- River Network: https://www.hydrosheds.org/products/hydrorivers#downloads
- AHP: https://bpmsg.com/ahp/
- https://ijahp.org/index.php/IJAHP/article/view/590
- Other references:
- https://www.cityresource.in/data.html
- https://www.sciencedirect.com/science/article/abs/pii/S2212420918314493?via%3Dihub
- https://link.springer.com/article/10.1007/s13201-018-0710-1
- https://onlinelibrary.wiley.com/doi/10.1155/2021/6128609
- https://www.omdena.com/blog/flood-risk-assessment-using-ahp-and-ml-togo