

Using Geospatial Technology to Investigate The Effects of Impervious Surfaces on Flooding in Mumbai

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ABSTRACT

Flooding is one of the most common and impactful natural disasters in the world. Some areas are devastated by floods on a yearly basis. One such area is the city of Mumbai, an extremely developed and populated coastal city in India. Mumbai faces several floods each year during its monsoon season from June to September. These floods are devastating to Mumbai which is India's financial capital. There are several theories as to why Mumbai floods so much and one theory is due to its high impervious, or artificial, surface percentage. Using geospatial technology such as satellite imagery from NASA worldview and Global Flood Monitoring System, this study focused on understanding the causes and effects of flooding in Mumbai and determining whether impervious surfaces cause more flooding in Mumbai. The flood event that was analyzed, the floods of July 2nd 2019, was also mapped. This study suggested that Mumbai's high impervious surface percentage and urbanization led to greater flooding which caused mortality and several economic damages. This research shows the potential for analyzing natural disasters with satellite technology and how to possibly prevent future damage from floods.

Keywords: Impervious, Flood Intensity, Precipitation, Rainfall, Floods, Urban, Mortality, Economic Loss

Introduction

Floods are some of the most impactful natural disasters in the world. Flooding happens when there is an overflow of water onto land that is normally dry and drains efficiently when wet. It is often caused by excessive rainfall. Any area that experiences excessive rainfall is vulnerable to flooding. Floods are the most common weather-related disasters and can be particularly dangerous (NOAA National Severe Storms Laboratory, n.d.).

In terms of mortality and property damages, floods are only behind tornadoes. Floods around the world cause over 40 billion dollars in damage annually. In addition, they kill more than a 100 people each year (Nunez, 2021).

Flash floods are a particular type of flood event where flooding occurs very quickly because the ground cannot absorb the heavy rainfall. Flash floods are typically more common in densely populated urban areas (NOAA National Severe Storms Laboratory, n.d.). This is because urban areas have a lot of impervious (not allowing fluid to pass through) surfaces that are unable to absorb flood water (Assessing the Impact of Impervious Surfaces on Water. Resources in Southern California, n.d.). Coastal urban areas are especially at risk because they are built and extensively developed in naturally flood prone areas. This is due to a growing population and people's desire to live near beaches and a coast (Riebeck, 2005).



Figure 1. An Example of a Coastal City

A major coastal city that faces floods is Mumbai. Mumbai is India's financial capital located in the state of Maharashtra. As of 2020, Mumbai has a population of 20,411,000 and is one of the most densely populated cities in the world (Kolb, 2019). Mumbai faces a harsh monsoon season from June to September that results in a lot of flooding (Ramudai, 2017). These floods bring the city to a pause multiple times each monsoon season. To contain flooding, Mumbai has built and is working on building more dewatering pumps (Ms, 2020). However, it is unknown whether these pumps will be enough to make up for the weak drainage systems, lack of natural flood absorbers, and extreme monsoon conditions (Srivastava, 2019).

The flood event that was studied in this paper occurred in Mumbai on July 1st 2019. This event was chosen because it was the heaviest rainfall in Mumbai in the last 14 years and a particularly devastating flood (Masih, 2019). This flood event spanned many days and begun on June 28th and reached its peak on July 1st



Figure 2. July 1st 2019 Flood in Mumbai

This study sought to map and analyze this flood event and the effect of its extent and duration on the disruption of the city's normal operation. This study also sought to determine whether impervious surfaces caused greater flooding in Mumbai on July 1st 2019. Some other causes of flooding, such as Mumbai's relative low elevation, were also investigated. These goals were accomplished through a variety of tools and figures.

Materials and methods

First, the main cause of the flooding needed to be determined and analyzed. Since this flood event was caused by torrential monsoon rain, the rainfall needed to be graphed. A time series as well as satellite images showing rainfall progression over a period of time were acquired. Using this information and the same dates, a time series for flood intensity was produced. Since there were multiple periods of rainfall, there was flood intensity variation over the observed time period. This resulted in three major flood peaks for which inundation maps for flood intensity were produced.

Visualizations/Satellite imagery:

NASA Worldview

(<https://worldview.earthdata.nasa.gov>)

is a tool from NASA's Earth Observing System Data and Information System (EOSDIS). It provides the capability to interactively browse over 900 global, full-resolution satellite imagery layers and then download the underlying data (*Worldview | Earthdata*, n.d.). Worldview was used to search for and visualize satellite images of flood related layers/maps in the Mumbai Area. These images were saved as a KMZ file (a file format meant for storing geographic data) and exported to Google Earth for further visual enhancement. Google Earth allows the overlaying of multiple layers and included roads and other landmarks in the final visualizations. The spatial resolutions for all the layers were checked and converted to meters. This was done for the purpose of scale compatibility and to ensure all the figures could be compared accordingly.

Selection of Layers/Maps:

Worldview provides several layers that can be used for flood analysis. The layers used in this paper were carefully selected based on what has been used in literature as well as their applicability to the Mumbai area. Furthermore, each layer selected had to fit and add to the three sections in this paper: causes, analyzing the flood event, and results of the flood event.

Overall Rainfall and Flood Detection Time Series:

Global Flood Monitoring System (<http://flood.umd.edu>) is a modeling system that uses real time satellite-based precipitation data to model and calculate information about floods, precipitation, and streamflow around the world (Wu et al., 2014, p. 2709). It was used to produce a time series plot for the three day rainfall accumulation

and flood detection/intensity for June 28th to July 4th. These dates were selected since they differed by three from the day of the most rainfall (July 1st) measured during the Mumbai flood event of 2019.

Flood Detection/Intensity maps:

Global Flood Monitoring System (GFMS) was used to produce maps showing the flood detection/intensity (depth above threshold) for Mumbai and the surrounding areas for the three flood peaks and a base map.

Hypothesis testing:

In order to understand whether impervious areas had a higher flood detection/intensity depth above threshold, three impervious and three natural areas around Mumbai were located using Google Earth. The coordinates were determined by using terrain in Google Earth and converted to decimal degrees. They needed to be converted since GFMS only accepts decimal degrees. These points were plotted in GFMS to produce time series for flood detection/intensity.

Results

Causes of flooding in Mumbai

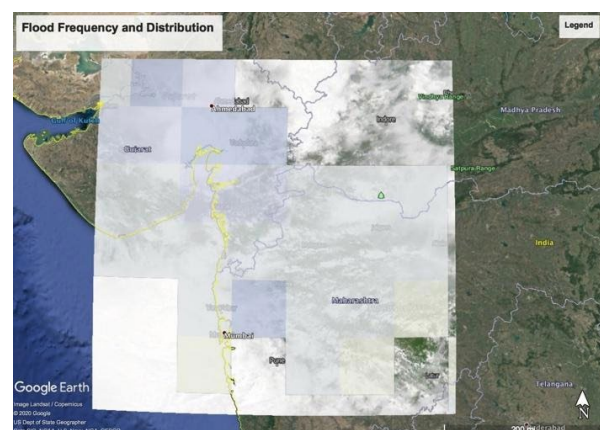


Figure 3. Flood Frequency and Hazard in Mumbai in 2000
Visualization of relative frequency and distribution in Mumbai and the surrounding area. Darker blue represents higher frequency and distribution and flood hazard. Mumbai has a value of 4 and 5. The scale is from 1-10 and it reveals the frequency of flooding as well as the relative distribution in a specific location.



Figure 4. Global Digital Elevation Map in Mumbai: The surface elevation of Mumbai and the surrounding area is depicted. Flat areas are dark green.

The main cause of flooding in Mumbai is torrential monsoon rain (Chandrashekar, 2019). This is why Mumbai has a relatively high flood frequency and distribution as shown in figure 2. However, other factors contribute to the severity and number of floods in Mumbai. As shown in Figure 4 Mumbai is extremely flat. Flat lands flood more since they allow more water to penetrate into the soil and stagnate on the surface when the soil reaches its water saturation capacity (Flooding - Water on the Land, n.d.). Another reason Mumbai floods is due to lack of reservoirs around it. Reservoirs help in flood management by storing flood water (River Management - River Flooding and Management Issues - GCSE Geography Revision, n.d.). However, they only protect from floods flowing from higher to lower elevations, not coastal floods. Mumbai, being India's most populated city and financial capital, is very urbanized and has a large percentage of impervious surfaces and buildings.

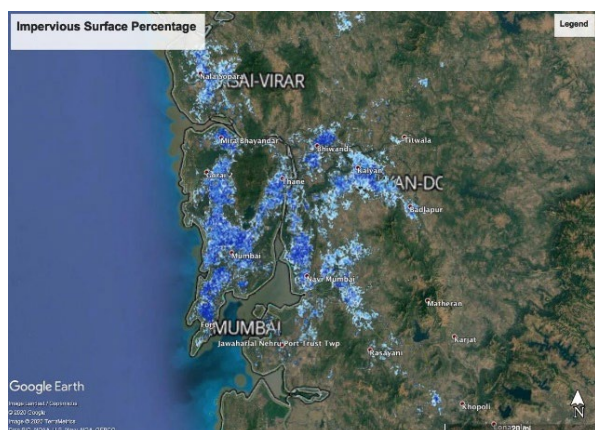


Figure 5. Impervious Surface Percentage of Mumbai in 2010. Visualization of impervious surface percentage in Mumbai in 2010. Darker blue areas represented higher percentages of impervious surface. Mumbai is at least 70% covered with impervious surfaces.

As shown in Figure 5, Mumbai is heavily covered with impervious surfaces. Impervious surfaces contribute to flooding because they do not absorb the flood water and cause runoff [3]. Mumbai also has several buildings and urban features. Urbanization contributes to flooding since it often takes the place of natural flood management services such as mangroves. In addition, it increases risk for economic damages of floods (Zhang et al., 2008, p. 2227).

Mapping and Analyzing the Flood event

The flood studied in this paper was the July 1st- 2nd flood in Mumbai in 2019. It was caused by extreme monsoon rainfall.

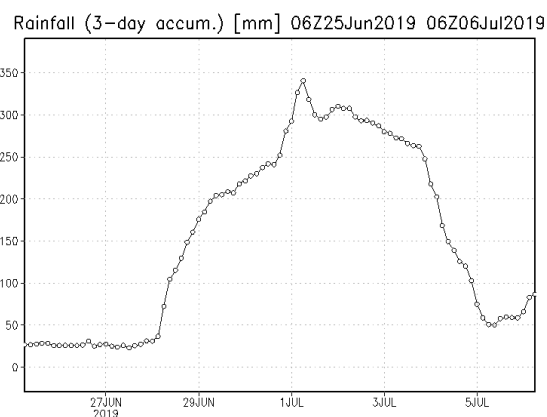


Figure 6. Three day rainfall accumulation in Mumbai from 25th June to 6th July 2019. Three day rainfall accumulation for Mumbai (19.06, 72.877) was plotted in 3 hour increments from 6am June 25th to 6am on July 6th 2019. The peak rainfall accumulation occurred at 6am on July 1st 2019.

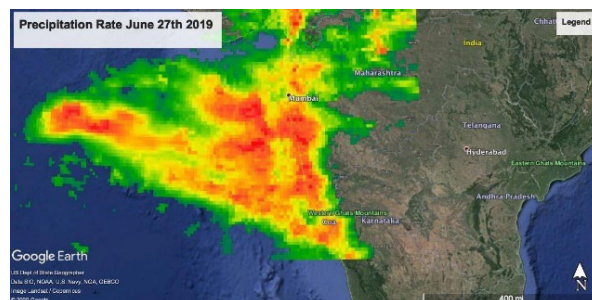


Figure 7. 1 day Precipitation rate in Mumbai and Surrounding area on June 27th 2019

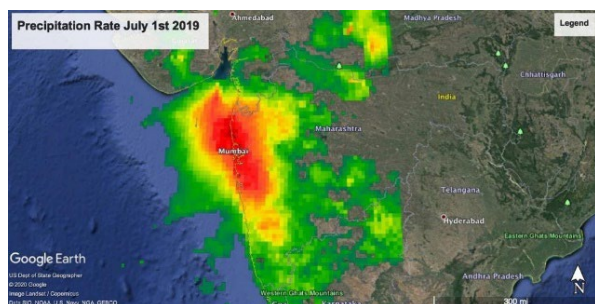


Figure 8. 1 day Precipitation rate in Mumbai on July 1st 2019
1 day precipitation rate in Mumbai on July 1st 2019. Mumbai had a precipitation rate of about 12mm/hour.

The storm started in the ocean as shown in Figure 7 and slowly centered around Mumbai in Figure 8. This correlates with Figure 6 as the rainfall is very slowly increasing on June 27 but rapidly picks up on June 29th since this is presumably when the storm begins to focus on Mumbai. This rainfall led to flooding over several days.

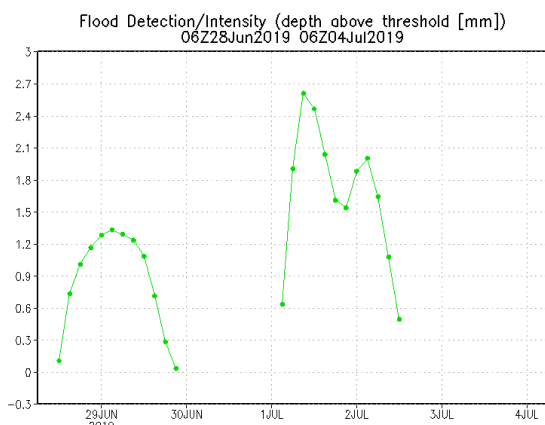


Figure 9. Flood detection/ time series in Mumbai from June 28th to July 4th 2019
The flood detection/intensity (depth above threshold) was plotted in 3 hour increments starting from 6am on June 28th 2019 to 6am on July 4th 2019 in Mumbai(19.06,72.877). There were 3 major flood peaks.

Inundation maps for the flood detection/intensity (depth above threshold) of the 3 flood peaks were produced in order to observe and analyze the change in flood intensity in different areas in the city of Mumbai.

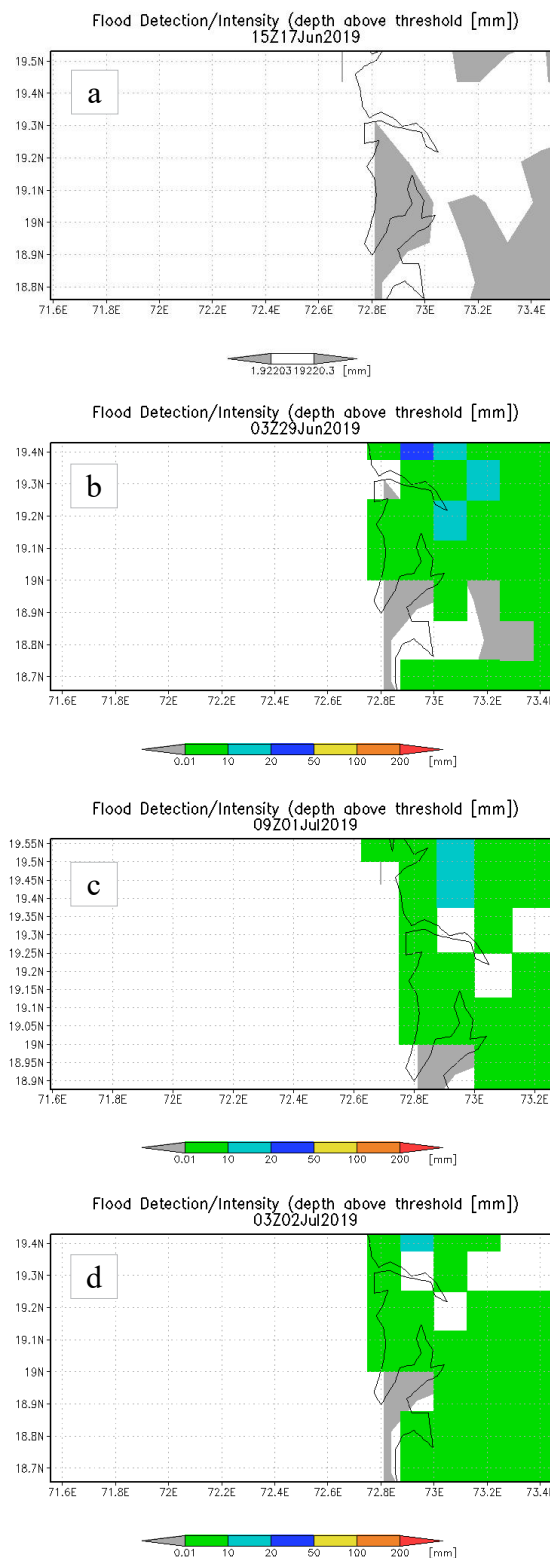


Figure 10. Flood detection/ time series in Mumbai from June 28th to July 4th 2019
The flood detection/intensity (depth above threshold) was plotted in 3 hour increments starting from 6am on June 28th 2019 to 6am on July 4th 2019 in Mumbai(19.06,72.877). There were 3 major flood peaks.

Damages caused by the Flood

This flood event had a significant impact on Mumbai in terms of mortality and economic loss. Damages caused by July 1st-2nd 2019 flood in Mumbai included 32 deaths, trains and flights suspended, train tracks and roads damaged, and building and wall collapses.

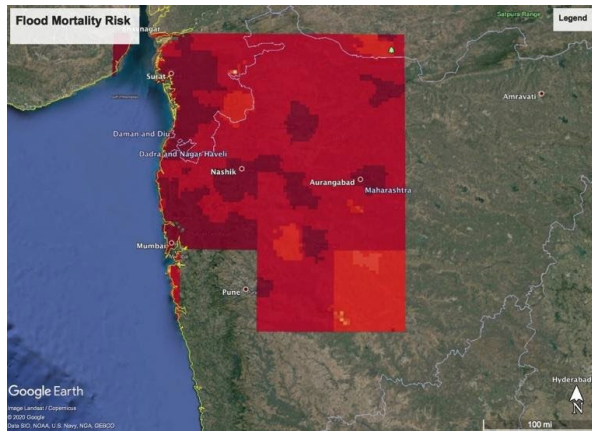


Figure 11. Mortality risk due to floods in Mumbai in 2000
Visualization of the loss due to morality because of flooding in Mumbai and the surrounding area. Darker red areas have a higher risk of mortality due to the flooding. Mumbai's mortality risk due to flooding is the highest on the scale, the 10th decile.

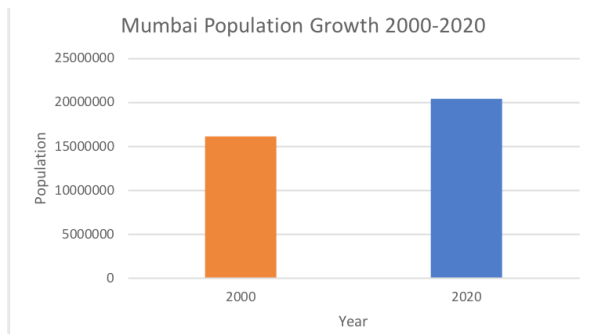


Figure 12. Mumbai population change from 2000 to 2020

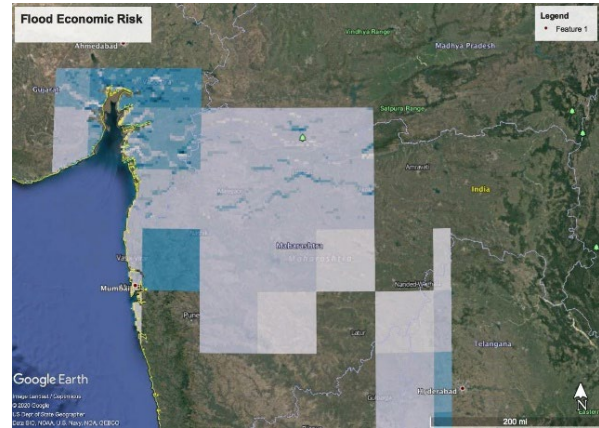


Figure 13. Risk of Economic Loss due to Floods in 2000
Visualization of the risk of economic loss because of a flooding in Mumbai and the surrounding area. The bluer areas represent areas more at risk of economic loss due to the flooding. Mumbai is in between the 5th and 7th decile.

In order to understand whether Mumbai's high impervious surface percentage played a role in its increased flood intensity, three impervious and three natural areas in the Mumbai area were selected and are shown in Figure 14 below. These sites were selected by analyzing spaces in the Mumbai area using google earth and picking three urban (impervious) and three natural (green areas).

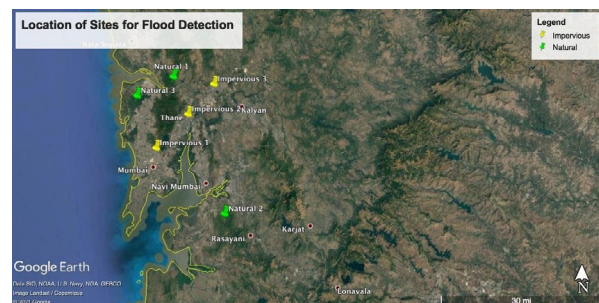


Figure 14. Location of points selected
Three impervious and three natural points located in and around the city of Mumbai. Green points are natural and yellow are impervious.

Time series for the flood detection/intensity from June 28th to July 4th 2019 were then produced for each of the points above. Natural in green and impervious in yellow.

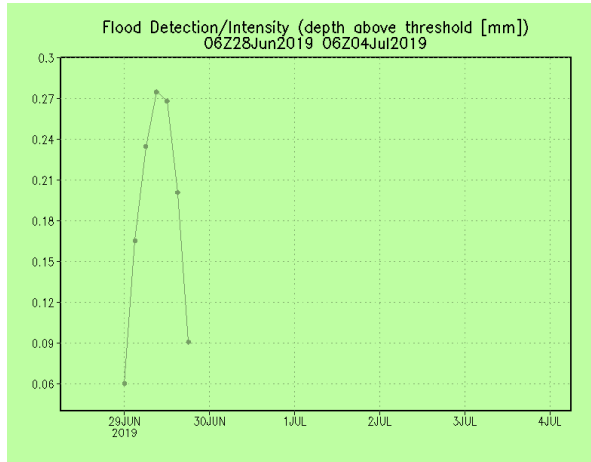


Figure 15. Flood Detection/Intensity at Natural 1 from June 28th to July 4th 2019
Flood detection/intensity (depth above threshold) time series for the point natural 1 in Figure 14 (19.30320278, 72.92777778)

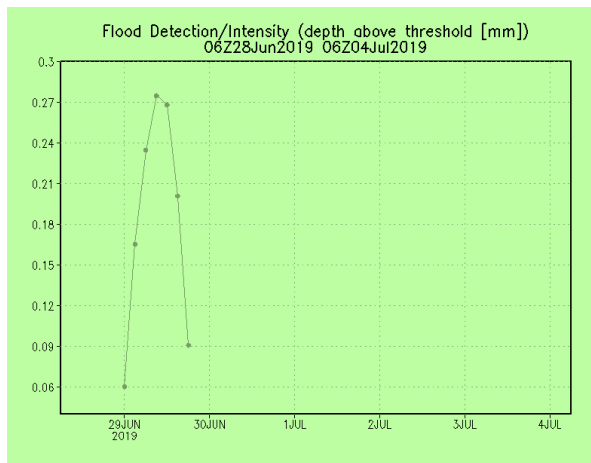


Figure 16. Flood Detection/Intensity at Natural 2 from June 28th to July 4th 2019
Flood detection/intensity (depth above threshold) time series for the point natural 2 in Figure 14 (18.9332, 73.0783)

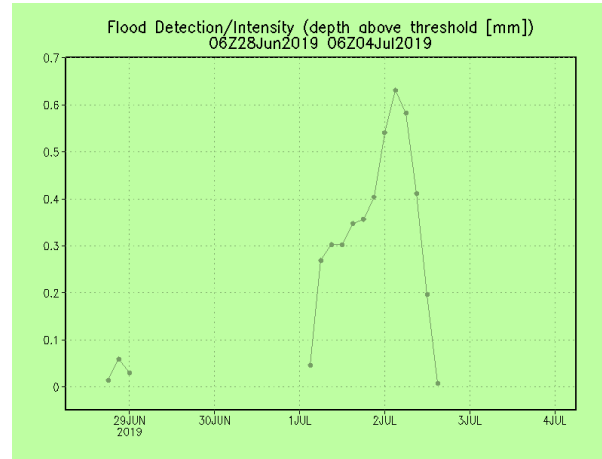


Figure 17. Flood Detection/Intensity at Natural 3 from June 28th to July 4th 2019
Flood detection/intensity (depth above threshold) time series for the point natural 3 in Figure 14 (19.2514, 72.82305)

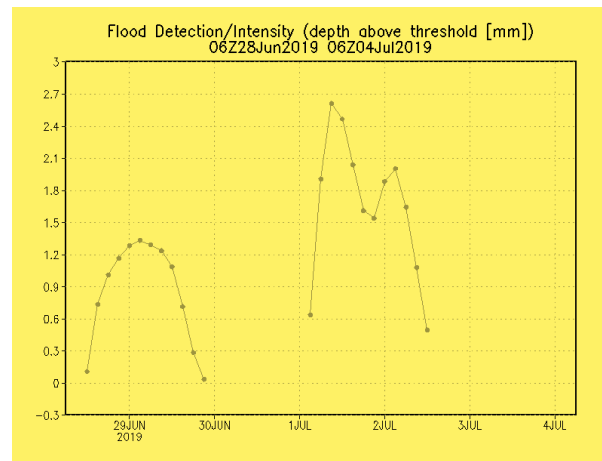


Figure 18. Flood Detection/Intensity at Impervious 1 from June 28th to July 4th 2019
Flood detection/intensity (depth above threshold) time series for the point impervious 1 in Figure 14

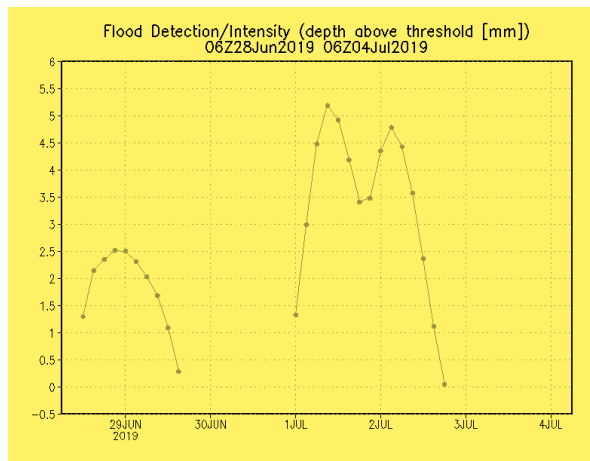


Figure 19. Flood Detection/Intensity at Impervious 2 from June 28th to July 4th 2019

Flood detection/intensity (depth above threshold) time series for the point impervious 2 in Figure 14 (19.20155278, 72.9708)

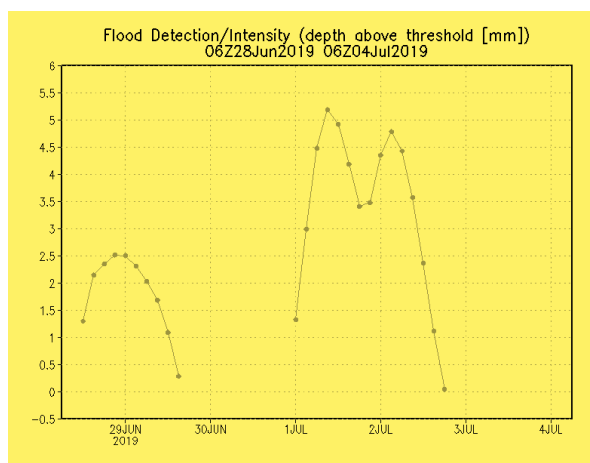


Figure 20. Flood Detection/Intensity at Impervious 3 from June 28th to July 4th 2019

Flood detection/intensity (depth above threshold) time series for the point impervious 3 in Figure 14 (19.2834, 73.044)

Discussion

Mumbai is significantly prone to the effects of flooding

Mumbai faces a very harsh monsoon season and often has multiple storms in a row as shown in this study. It is presumably not able to cope with many consecutive storms due to an old drainage system as well as depletion of natural flood absorption techniques such as preserving or planting mangroves

(Chandrashekhkar, 2019). Furthermore, Mumbai's terrain makes it more susceptible to floods. Mumbai has mostly flat, coastal terrain. Since flat lands allow for more water to penetrate into the soil, by the time the second major rainfall event occurs, the soil water storage capacity is already at the maximum. This causes more flooding and is presumably the reason that the second and third flood peaks are greater than the first in the time series graphs shown in this paper. Even though Mumbai has reservoirs, they do not protect Mumbai from storms coming from the ocean. Finally, Mumbai is immensely covered with impervious surfaces which contribute to flooding (Assessing the Impact of Impervious Surfaces on Water Resources in Southern California, n.d.).

Mumbai is prone to damages of flood events

Mumbai is prone to damages from floods and suffered many damages from the July 1st-2nd 2019 floods. Since Mumbai has such a high population density, it is susceptible to death due to floods as shown by Figures 11 and 12. Mumbai also has many old buildings and slums. These are especially vulnerable to floods and often have wall collapses. Furthermore, since Mumbai is the financial capital of India, it faces a risk of economic loss through disruption of public life (Srivastava, 2019). This is supported by the fact that this flood caused flights and trains to be cancelled.

Analyzing the flooding and rainfall

The floods of July 1st, 2019 depict a classic monsoon storm in the city of Mumbai. A storm comes in from the ocean and causes mild rainfall for a few days resulting in a small amount of flooding which corresponded to the first flood peak in Figure 9. Since Mumbai has a weak drainage system as well as few natural flood absorbers, this initial rainfall often depletes flood water storage capacity. Then, when other storms center around Mumbai and cause extreme rainfall, the subsequent flood peaks are much more intense as shown in Figure 10.

Impervious surfaces caused a greater intensity of floods

Impervious surfaces had a greater flood detection/intensity (depth above threshold) than the natural surfaces as shown in Figures 15-20. The three

natural sites were all within 40 km of Mumbai's city center with Natural 1 and 2 being much closer. Natural 1 was a natural park, Natural 2 was a natural area containing mangroves, and Natural 3 was an area surrounded by forests and waterfalls. Natural 3 also had a higher elevation as compared to the other points. All 3 distinct natural sites had significantly lower flood detection/intensity values than all three impervious sites. The site Natural 1 only had one flood peak which was unusual and warrants further investigation. Natural 2 and 3 had very small first flood peaks as compared to the impervious sites. This is presumably because the surfaces absorb most of the water from the first major rainfall event but cannot absorb all from the second rainfall event. Impervious surfaces, on the other hand, can only absorb very little to none of both flood events. As a result, all their flood peaks are relatively large. Figures 15-20 do not exactly correspond to the impervious and natural areas depicted in Figure 5. This is because the pixel size of the flood detection/intensity map from the GFMS is very coarse (12x12 km²) compared to the city footprint and the size/shape of the natural land cover patches (Wu et al., 2014, p. 2694). In contrast, the impervious surface layer from NASA Worldview has a pixel size of 30 m. This is why the GFMS maps do not align with the impervious surface one. Furthermore, the city of Mumbai is an elongated shape with a width of about 11km. This is another reason why the GFMS, with a pixel size of 12 km, does not align perfectly with the map. In addition, a limitation to this study is the potential bias in selecting the natural and impervious sites since they were not randomly selected.

Selection of Layers and Limitations of Study

There were other layers that could have also been used in this paper. One such layer is the soil moisture (SMAP) layer. If included in this paper, this layer would be in the mapping and analyzing the flood event section. This layer was not selected because the rainfall and flood detection/intensity layers are deemed more effective. Some limitations of this study are the differing temporal and spatial resolutions used. NASA Worldview does not provide images for every year. As a result, this study had to utilize various temporal resolutions. In addition, differing spatial resolutions also had to be used at times causing a mismatch in scale between the different map layers.

Conclusion

This study hypothesized that Mumbai's large impervious surface percentage caused high flood detection/intensity. This study also investigated the causes of flooding in Mumbai using satellite imagery. Some of the causes included flat lands, impervious surfaces, and torrential monsoon rain. One reason why Mumbai faces harsh floods during the monsoon is due to multiple storms within a short time period. This was true for the flood event studied in this paper, the July 1st 2019 floods. The July 1st 2019 flood devastated the city through economic loss and mortality. The results support the hypothesis since three selected impervious sites all had 3-6 times higher flood intensity than the three selected natural sites.

This study adds onto previous research on the floods in Mumbai by studying a new flood event and going more in depth as to the cause of flooding in the Mumbai. There are a few options for future research for this study. One is to re design this study for another coastal urban city in India that is affected by monsoons and compare to the results for Mumbai. Another would be to design and research more flood management techniques and technology. To further strengthen the statistical significance of the findings in this study, more natural and impervious points will also need to be selected for comparison. Overall, this study demonstrates the vulnerability of Mumbai to the effects of flash floods due to a high impervious surface percentage.

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Appendix

Name of Layer	Time	Spatial Resolution(m)	Source
Impervious surface percentage	2010	30	https://sedac.ciesin.columbia.edu/data/set/landsat-gims-x1
Flood Hazard: Economic Risk	2000	4600	https://sedac.ciesin.columbia.edu/data/set/ndh-flood-proportional-economic-loss-risk-deciles
Flood Hazard: Mortality Risk	2000	4600	https://sedac.ciesin.columbia.edu/data/set/ndh-flood-mortality-risks-distribution
Flood Hazard: Frequency and Distribution	2000	4600	https://sedac.ciesin.columbia.edu/data/set/ndh-flood-hazard-frequency-distribution
1 day Precipitation Rate IMERG	June 27 th and July 1 st 2019	2000	https://disc.gsfc.nasa.gov/datasets/GPM_3IMERGDF_06/summary
Global Digital Elevation Map(Terra/ASTER)	July 1 st 2019	30	https://pdaac.usgs.gov/products/astg/tmv002/
Flood Detection Intensity maps	29th June, 1st July, and 2nd July 2019	12,000	http://flood.umd.edu
Reservoirs	July 1 st 2019	1,000	https://sedac.ciesin.columbia.edu/data/set/grand-x1-reservoirs-rev01

Table 1. Table of reference used for visualizations in paper