Flooding observations in Rotterdam: mapping of flood-prone locations, flood vulnerability and risk analysis

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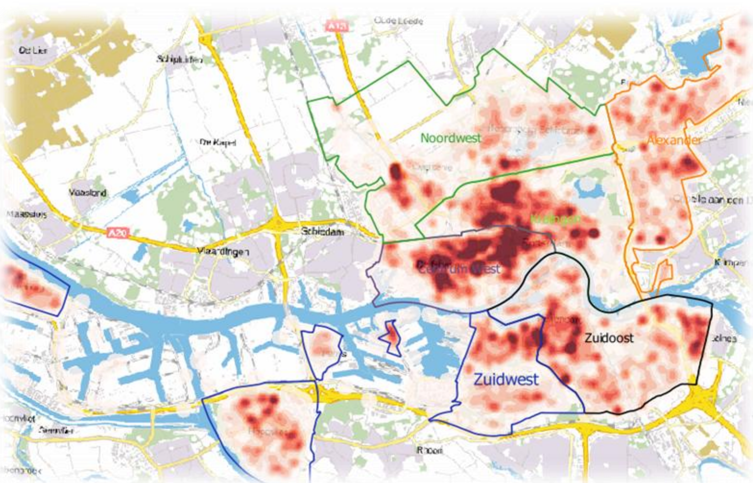

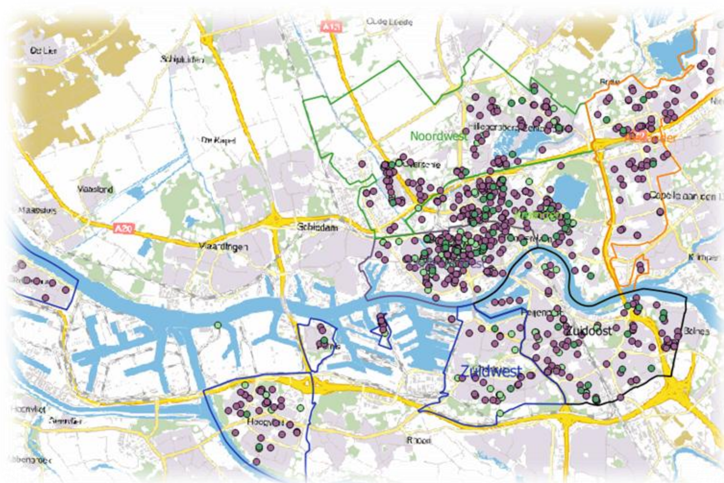

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Abstract

This thesis focuses on identifying flood-prone locations, flood vulnerability and analyzing risk for the Municipality of Rotterdam. Municipal call center data of flooding complaints from 2012-2016 are investigated to identify the most flood-prone locations, which are called hot spots. This is performed by creating heat maps of the flooding record locations. The most dominant hot spots for multiple analyses are all situated in the sub districts of 'Rotterdam Centrum', 'Delfshaven' and 'Noord'. Most flooding records are related to gully pots (≈55%), followed by sewer related problems (≈20%). Flood vulnerability is investigated by analyzing the influence of amount of inhabitants and degree of imperviousness on the hot spot locations. Both factors are involved in the origin of the hot spots. Investigating the influence of rainfall on flooding incidents pointed out an exponential relationship. From comparing differences in resulting flooding records for heavy/extreme rainfall events and cloudbursts, it can be concluded that Rotterdam's drainage system is better capable at handling short heavy bursts of rainfall than consecutive hours of rainfall. The influence of seasonality on flooding incidents has also been investigated. There do appear to be seasonal patterns, which can be linked to blockages of gully pots by leave fall. In the risk & asset management analysis, asset maps related to infrastructure are created. They are used to calculate risk levels, based on the company values matrix of the Water Management department of Municipality of Rotterdam. The lower elevation of Rotterdam's city center and surrounding downward slopes, which have been identified from the created elevation map, might contribute to the increased flood vulnerability and hot spots in the city center area.

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Introduction

Urban flood risk & management

Urban flooding is caused by a couple of factors, which are both natural and human (Tingsanchali, 2011). Heavy rainfall in combination with high building densities and impervious surfaces are examples of factors driving urban flooding (Gaitan et al., 2016; ten Veldhuis et al., 2011). Urbanisation and climate change intensify urban flooding incidents, as peak flow volumes will be enlarged due to heavier rainfall and larger impervious surfaces (Semadeni-Davies et al., 2008). Unfortunately, the large impervious surfaces and created drainage structures increase the speed of the surface runoff flow, reducing the time in which the peak volume enters the urban drainage system (Griffiths, 2016). All of these aspects lead to bigger urban flooding risks.

Risk can be expressed as hazard multiplied by vulnerability. Here, hazard is defined by the magnitude of flooding, caused by flooding intensity and duration. Vulnerability is defined by the degree of which people and infrastructure in urban environments are susceptible to impacts of urban flooding. These impacts can do serious damage to infrastructure, people and the environment. Economic losses are a consequence (Tingsanchali, 2011; Cherqui et al., 2015). Risk can be reduced by handling urban water with a sustainable approach. One way to achieve a sustainable approach is integrating urban water use with environmental- , industrial- and agricultural water use. Since vegetation facilitates infiltration, it means it can be used to reduce the impact of peak volumes entering the urban drainage system. Another advantage of using vegetation in urban environments is that they reduce climate change induced rising urban temperatures by transpiration processes. This enhances living conditions of urban environments. Creation of additional storage for storm water creates opportunities for water re-use, for example for irrigation purposes (Ursino, 2015). Vegetation and additional storage creation are examples of Sustainable Urban Drainage Systems (SUDS) components. These different components are as follows: source control; conveyance; treatment and attenuation. Source control reduces speed and total volume of incoming runoff headed in downstream direction. Examples are green roofs, infiltration trenches and permeable pavements & roads. The conveyance component is responsible for transport of all collected water in the downstream direction, ideally in a slower manner than conventional transport methods. Treatment and attenuation represents the last component of a sustainable urban water system, in which stress on the system is relieved by retaining water, instead of allowing everything to directly flow to treatment facilities or pumping it into open water (Griffiths, 2016).

Quantifying risks of urban flooding can be performed with different methods. A common approach is hydrodynamic modelling of urban drainage systems (ten Veldhuis, 2010). This type of approach allows for identification of flood prone areas and insufficient pipe capacities at predefined (heavy) rain intensities (Cherqui et al., 2015). However, hydrodynamic models are prone to high uncertainties and are therefore usually too inaccurate to evaluate historical events. Calibration of hydrodynamic models and quantification of uncertainty can help improve the accuracy of these models. Still, such a model will deviate from reality, as factors like sedimentation in pipes or corrosion happening over time are difficult to capture (ten Veldhuis, 2010). These small-scale processes can however lead to failure of the system components and hence urban flooding. Human errors play a role in these small-scale processes as well (ten Veldhuis et al., 2011). For example, flooding problems related to blocked gully pots or pipes can be prevented by better maintenance (Cherqui et al., 2015). While these small-scale degradation or human error processes are not captured in hydrodynamic models, they are captured in historical data. For these reasons, quantifying risks of urban flooding can be performed based on historical data of flooding incidents and frequencies. This method is performed by Cherqui et al. (2015), who base their urban flooding risk analysis on historical intervention data of flooding incidents in the French city of Bordeaux. They performed a spatial analysis based on this data and successfully created hazard maps showing the most flood prone locations in the city. Another urban flooding risk analysis, performed by ten Veldhuis (2010), is based on historical call center data of two Dutch cities. This call center data, which was obtained from the municipalities, consists of complaints of citizens about urban drainage problems. Based on this data, dominant failure mechanisms of the urban drainage system were identified and flooding probabilities were calculated. It followed from the investigation that hundreds of flooding incidents per year are related to human errors and component failures (ten Veldhuis et al., 2011). This validates the effectiveness of using historical data to analyse urban flooding risks.

Urban flood risk assessments can be used to improve urban flood management. An important aspect of urban flood management is reducing losses. These losses can be economic, physical, social and environmental. They can be reduced by trying to prevent urban flooding as much as possible (Tingsanchali, 2011). In doing so, it is key that risk hot spots in a city are identified, as these are the areas where most damage can be done. It is important to protect occupational functions and to minimize vulnerability of those important areas. Optimizing and maintaining the overall functioning of a city is another way to express urban flood management. A city should utilize opportunities and look for the best solutions in order for the benefits of the solutions to outweigh the costs. Therefore, if applicable, multi-functional solutions can be a good step towards efficient urban flood management (Zevenbergen et al., 2010). Based on urban flood risk assessments, operational strategies can be formulated to prevent flooding incidents. There are two types of strategies: corrective and preventive. Corrective strategies include fixing a problem once it has already happened. Preventive strategies include scheduled repairs, which comes down to regular monitoring and inspection (ten Veldhuis, 2010). From the research of ten Veldhuis (2010), it appeared that gully pot blockages form the main failure mechanism of flooding in the case study cities. An example of a preventive strategy to reduce these flooding incidents is preventive scheduled cleaning of gully pots. The most important failure mechanism found in the research of Cherqui et al. (2015) was also gully pot blockage. The authors came up with a similar preventive strategy as ten Veldhuis (2010). Overloading of the system due to heavy rainfall did not come up as a big constituent of flooding problems.

Water management in Rotterdam

Rotterdam is not only the second biggest city of the Netherlands, it also has one of largest harbours in the world and a history of harnessing and draining water in order to expand. From this follows the importance of water management in the municipality. The city consists of numerous canals and a couple of man-made ponds. Rotterdam also has an extensive drainage system, which consists of sewage pipelines, pumping stations and pressurized pipelines going to the treatment plants. Eventually, all treated water is discharged into the Nieuwe Maas river. If there is too much stress on the urban drainage system in times of heavy rainfall, excess water can be discharged over a multitude of overflow points. This is performed to prevent water from ending up on the streets in the city. Since climate change will cause the weather extremes to become more extreme, rainfall will intensify as well as droughts in the summer. This means the Municipality of Rotterdam has to adapt the water system to make it more robust. To achieve this, they aim to increase water storage capabilities, separate wastewater from rainwater and enhance groundwater control. With increased water storage capabilities, the water system will be able to coop better with excess water from heavy rainfall events. Examples of such (multi-functional) solutions, are the underground water storage Museumpark, the Roof Park and the Water Square (Benthemplein). By separating wastewater from rainwater, the effluent of the water treatment plants remains of good quality, which means that no harm to the environment is done (Water Atlas, 2012).

Water safety is one of the important subjects of Rotterdam's Waterplan (2013). Urban flooding risk management is central in this. Water safety should be guaranteed based on a three layer approach: prevention, spatial planning and disaster management. One of the targets for the upcoming years to increase water safety is improving the dikes and flood defences. *Water quantity* is also addressed in the Waterplan. Enhancing water quantity is often approached by the method: 'retain, store, drain', giving a structured approach to making the water system more sustainable and robust. This approach is quite similar to the description of different SUDS components by Griffiths (2016). To check whether the urban drainage system can handle certain heavy rainfall events, the Municipality of Rotterdam is developing a model with 3Di software. As described above, objectives to increase in temporary water storage and enhanced groundwater control are included in Rotterdam's Waterplan. Important in increasing temporary water storage is making it attractive to the public and adding value to the public spaces. A general approach for this is making the city greener. Green roofs are an example of this, which is a solution implemented on different locations in Rotterdam. *Water quality* of the water bodies should be enhanced in the upcoming years. A target to reach optimal water quality is clear and plant rich water. The quality of all water bodies in the city should meet the targets of the European Water Framework Directive. The *urban sewage system* should be improved by a cooperation between Municipalities and Water Boards. The aim of this cooperation is reducing costs and improving sustainability and quality of the system.

Preventing all urban flooding events is impossible. Water on the streets is therefore a quite normal event. After all, the urban drainage system of Rotterdam is designed based on an optimum of costs and estimated occurrence of water on the streets. The Municipality finds water on the streets every now and then acceptable. However, as a result of extreme rainfalls, water nuisance can occur. Water nuisance can lead to economic damage and risky situations for traffic and public health. Examples of this are flooding of buildings, sewage water on the streets and floating manhole covers. This has to be prevented as much as possible (Gemeentelijke aanpak regenwateroverlast, 2015). The company-value matrix is used to express what type of flooding risks the Municipality finds acceptable (Figure 43, Appendix C). This matrix is produced by the City Management department (Stadsbeheer). City Management's most important goals are creating a safe and clean city environment. The Water Cluster sub department contributes to this aim by focusing on the prevention of urban flooding problems. Risk in the company-value matrix is expressed as impact multiplied by probability or frequency. Risk is determined for each of the company values, which are: availability, safety, environment, living space quality, reputation, law & regulations and economy. The actual risk is expressed as a consequence for each of the company values and it is expressed whether this consequence is acceptable or not. This company-value matrix can be used to analyse flooding risks in the city and what consequences this can have on important assets of the city.

As mentioned above, the Municipality is developing a 3Di model to determine where the areas vulnerable to flooding are in the city. Call center data can be valuable to crosscheck the results from the hydrodynamic model. Processing this data and sorting it on disturbances caused by flooding could lead to the determination of vulnerable hotspots in the city. This makes the call center data interesting to investigate.

Objective of thesis

The objective of this thesis is to investigate flood complaint data (call center data) for the determination of flood-prone locations, flood vulnerability and risk to important assets of the city of Rotterdam. To give the investigation a structured approach, a set of research questions has been formulated. These are as follows:

1. *Where in the city are flooding incidents encountered and what is their spatial distribution?*
   This will be derived from call center data ranging from 2012 to 2016. This data is obtained by the Municipality from civilians that encounter flooding problems in Rotterdam. Every call or message contains a description of the encountered incident and a location. First of all, the call center data has to be screened to check if the complaints match the problem categories that have been predefined by the Municipality. Then, this data can be used to create a spatial distribution of the incident locations. Sensitive areas can be identified based on the distribution of incident locations. High density areas have a higher flooding probability and can be defined as 'hot spots'. Heat maps can be used to locate and visualize these sensitive areas. Afterwards, a comparison will be made between the distribution of the amount of inhabitants in different districts in the city and the amount of complaints in those districts, to see how they affect each other. This will be followed up by a specific investigation about where most flooding problems in buildings are encountered.

2. *What are the dominant flooding problem categories, their failure mechanisms and what is the origin of flooding hot spots?*
   Based on the amount and problem type of flooding incidents, it can be determined which categories and failure mechanisms are dominant throughout the investigated years of 2012-2016. The statistics of the flooding records will therefore be investigated in this chapter. The relative contributions of each problem category will be mapped. Also the amount and type of flooding incidents for each identified hot spot will be investigated to learn about the origin of each hot spot. It can then be answered why hot spots are found where they are.

3. *What is the correlation between flooding incidents and rainfall?*

Investigating flood incident data after different rainfall event allows for checking what the influence of rainfall is on flooding. This can be done by selecting different type of events, like no rainfall, light rainfall and heavy rainfall conditions. By determining the reported flooding incidents at no rainfall conditions, a baseline of flooding incidents can be quantified that is not caused by rainfall. This can then be taken into account when handling the reported flooding incidents at light and heavy rainfall conditions. In this way, right conclusions can be drawn on the sensitivity of the urban drainage system to different intensities and durations of rainfall. A spatial distribution of flooding records received after specific heavy rainfall events can be created to see if there are any hot spots in the city that appear to be extra vulnerable to heavy rainfall. In this analysis, emergency (112) call records will also be taken into account.

4. *What is the correlation between flooding incidents and seasonality?*
   Seasonality is the driver behind the presence of leaves on trees or on the surface in the city. These leaves can cause gully pot blockages, which increase the amount of flooding incidents. If a specific investigation is performed on the amount of gully pot records throughout the months in the time interval of 2012-2016, perhaps it is possible to observe a seasonal pattern. This seasonal pattern can provide information about higher or lower gully pot related flooding incident probabilities. Also, it might be possible to distinguish between human or natural factors behind the flooding incidents.

5. *Where are the vulnerable hot spots in the city, taking into account occupational functions?*
   A risk analysis will be performed to find the most vulnerable hot spots in the city of Rotterdam. For this analysis, the created heat map will be taken into account as well as the company-value matrix of the Municipality. Besides this, an infrastructure & traffic map can be used to identify key roads and an elevation map to identify low points or depressions. As a result, potential bottlenecks in the city can be identified. This information is valuable in the creation of the improved asset management strategies.

These research questions will be used as a guideline for the upcoming chapters in this report. After the elaboration of these chapters, a sensitivity analysis will be performed to express uncertainties in the research and their influence on the quality of the results. Finally, a discussion and conclusion chapter will follow to summarize all key findings of the investigation and to draw conclusions based on it.

Required data and software

A variety of data sets and software is required for the investigation as introduced above. An important part of the investigation is sorting and processing of call center data. This call center data will be obtained from the Municipality and investigated over the last five years (2012-2016). Data about the urban drainage system of Rotterdam is important to make a link between flooding incidents and the present assets at the flooding locations. This is especially important for the asset management analysis that will be performed in the fourth chapter. This data will also be obtained from the Municipality. Rainfall data can be retrieved from the KNMI website or from data from the Municipality. The

Municipality has rainfall data of local rain gauges. Rainfall data is needed to investigate the correlation between (heavy) rainfall events and flooding incidents.

The software that will be used for the mapping of flooding locations and spatial analysis is QGIS/ArcGIS. GIS stands for Geographic Information System. QGIS is free open source software that is great for visualizing, editing and analysing geospatial information (QGIS, 2016). ArcGIS is similar, but it is mainly used by corporations and it requires a license. Since ArcGIS is available at the Municipality of Rotterdam where the investigation will be performed, both QGIS and ArcGIS will probably be used. Microsoft Excel will be used to process and sort the large amount of call center data. The Municipality of Rotterdam recently started using Lizard software, which is used to characterize rainfall events. Currently, the main input of this software is KNMI rainfall data. Also rainfall data from local rain gauges can be checked in Lizard.

1. Mapping of flooding incidents and flood prone locations

Call center data from the Municipality can give insight into the water sensitive areas of the city of Rotterdam. This information can then be used to tackle potential vulnerable areas and to make the urban water system more robust. Generally, all complaints from the Rotterdam call center data have a serial number, date, incident location and incident description. It is assumed that all (complete) flooding records correctly represent urban flooding issues and that they can therefore be used to make a representable analysis of flood prone locations. The decision is made for this part of the research to focus on the last 5 years of data. This means that data from 2012 to 2016 will be included in the analysis. The call center data is obtained through GIS shape files from the data base of the Municipality. The flooding complaints are all categorized by the main category of 'Water and Sewers'. Within 'Water and Sewers', there is a subdivision in multiple categories, which represent different causes of the complaints. These categories can be found in Table 1.

Category number	Category name	Category description
1	Groundwater	flooding caused by a too high groundwater table
2	Sewer	flooding of sewers by system overload or component failure
3	Lack of drainage	when there is ponding of water at the surface as there is no access to a drain
4	Malodour	usually related to sewer problems (when overloaded or blocked)
5	Pumping station	usually a malfunction of the pump or pressurized pipe
6	Gully pot	can be blocked or broken causing pools of water to reside on the surface
7	Flooding in building	usually related to flooding of basement, ground floor or garden which can be caused by different events (for example ponding on the streets or groundwater)
8	Flooding - other	random causes that cannot be related to above

Table 1: Call center data categories of flooding incidents

There are some categories that can be related to others. For example, 'malodour' can often be related to failure of a sewer system component. 'Flooding in building' can usually be related to 'sewer' pipe or 'gully pot' blockages, 'groundwater' or 'lack of drainage' (ponding on the street). 'Flooding in building' is not a failure mechanism itself. However, as it is an important nuisance, it is taken up in the analysis of the flooding incidents. The same applies for the other categories. There is one exception, which is 'flooding –other'. Since only 2012 and 2014 have this category with not more than one or two entries, it is considered irrelevant and not taken up in the analysis. This means that category 1 to 7 are used for the analysis.

Unfortunately there are no maintenance records that can be used to validate whether a call record is properly assigned to the category that is saved in. In an attempt to increase the accuracy of the categories, all records within the different categories are filtered. Text filters are used to reassign any misfits. For example, it happens that a gully pot blockage is assigned to 'lack of drainage' or 'sewer'. These type of misfits are filtered out and put in the right category based on the description of the record. After analysing each category, all corrected categories are merged in one list again to investigate any lack of data components. Quite a lot of call center records have a zero as the house number of the address. While this is incorrect, the records generally have a X and Y coordinate to indicate the precise flooding location. A house number that equals zero is therefore not a problem. However, quite some records do not have these X and Y coordinates. The decision is therefore made to not take these records up in the further analysis. Also, records lacking a problem description are deleted from further investigation, as there is no way of validating that these records have been assigned to the right category.

All of the filtered flooding incident records add up to 23609 data points, which are plotted in QGIS. To give an overview of what this looks like for the whole Municipality of Rotterdam, Figure 1 is created. This figure gives an idea about the scale and distribution of all of the flooding incident records. There are so many, that no clear results can be drawn based upon this map.

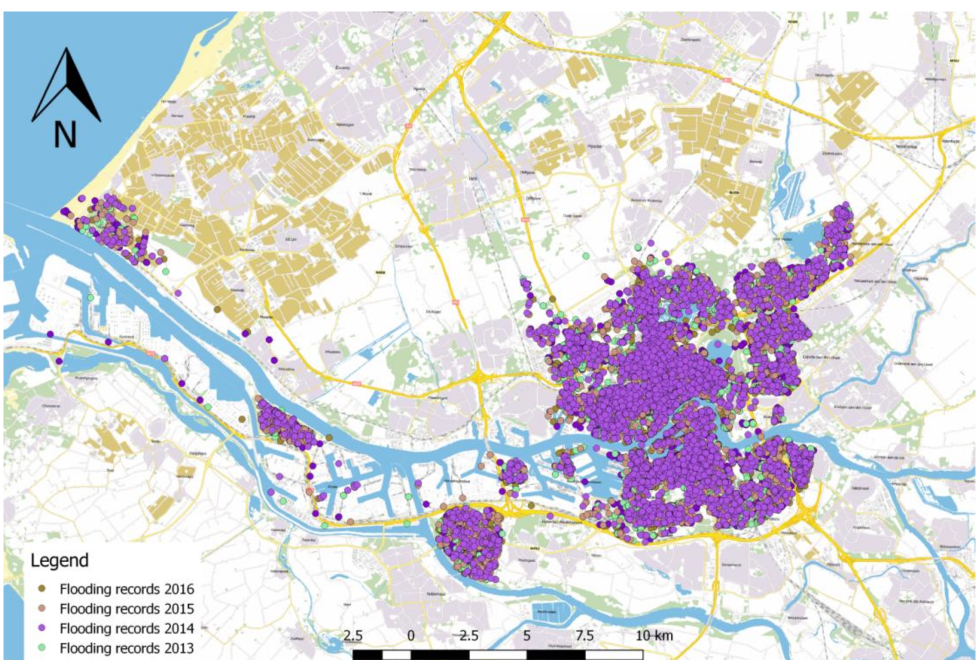

Figure 1: All flooding incident records for 2012-2016 in the Municipality of Rotterdam

To be able to find hotspots, a density map will be constructed that highlights clusters of points that are in close proximity of each other. This can be performed with the QGIS plugin "Heat map". According to QGIS (2017), the heat map plugin uses a kernel density estimation to create a density raster layer based on the input point data. The input point data are all of the call center data points combined, which means all years together. According to Fortmann-Roe et al. (2012), the kernel density estimation is a popular technique to calculate the distribution of a set of points. This function is given by Formula 1:

$$f(x) = \frac{1}{n} * \sum_{i=1}^{n} K \frac{x_i - x_0}{h} \quad (1)$$

Here, f(x) is the density function that calculates the density of the raster at each pixel. n is the amount of sample points (the flooding locations). K is the Kernal Function that gives a weight to all sample points x_i at every given point x_o. h is a smoothing parameter that determines the bandwidth around x_o. In the QGIS heat map plugin a radius has to be set, which is used to control the bandwidth around the sample points. The radius is set to 250 meters, which gives enough accuracy to make distinctions between individual hotspots, instead of seeing larger blurs. The data of all years (2012-2016) is combined for the creation of a qualitative heat map. Figure 2 shows the resulting image. The dark red areas indicate the areas that appear to be most prone to flooding, based on the highest density of flooding records. These locations are mainly situated in the district Centrum West and Kralingen Noord. There are some other relatively smaller locations that are also quite dark red, meaning that the presence of recorded flooding incidents is higher here as well.

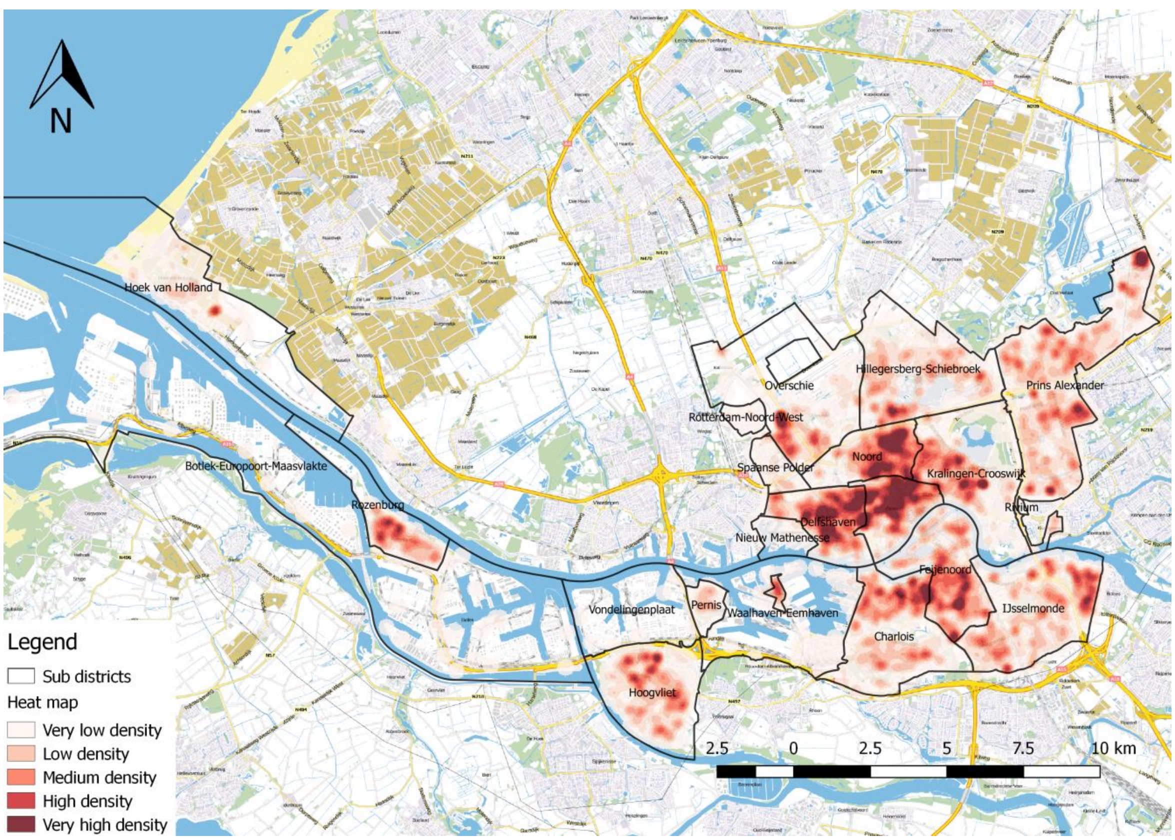

Figure 2: Qualitative heat map of flooding incident records (2012-2016)

To learn more about the most flood prone locations based on the heat map, a filter is applied that extracts the locations with the highest densities. This filter is set to extract the top 10% highest density locations. Also, to delete all of the small hot spots on the map that consist out of only a couple of pixels, all hot spot areas smaller than 0.05 km^2 are removed. In total there are 19 remaining hot spots in different districts. Figure 3 shows them on a map. To be more precise about their locations, a layer of sub districts has been added to the map. The largest cluster of flood prone hot spots are situated in the sub districts of 'Rotterdam Centrum', 'Delfshaven' and 'Noord'. Another smaller cluster can be seen in the sub districts of 'Charlois' & 'Feijenoord'. There are more small hot spots in various locations of the Municipality. These small hot spots can for example be found in Kralingen-Crooswijk, Overschie, Ijsselmonde and Prins Alexander.

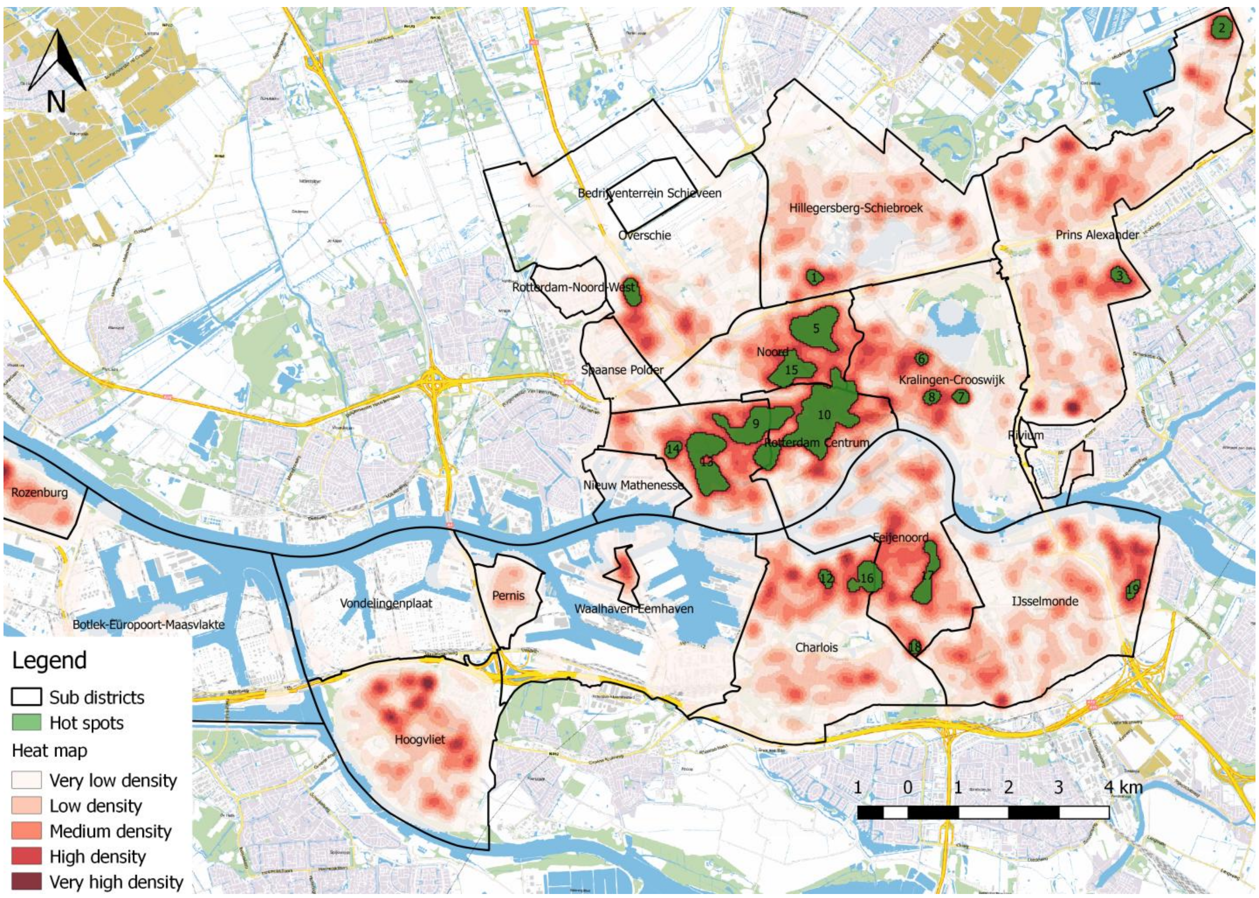

Figure 3: Map of flooding incident hot spots, based on heat map

The overview that Figure 3 gives of the hot spot locations are based on all of the flooding records of 2012 to 2016. This is an important image to understand which areas are in general the most prone to flooding. However, from all of the problem categories, flooding in building is the category that has the biggest direct impact, as it guarantees nuisance and economic damage. Flooding of buildings is therefore a big problem for the Municipality. Therefore, it is valuable to investigate flooding in building records independently. In this investigation, emergency (112) call records will be included as well. It is a common practice for civilians to call the emergency number if buildings are flooded, instead of contacting the Municipality. The 112 records are therefore valuable to include in the analysis. All of the flooding in building related records from the Municipality (1015 in total) are plotted for the years 2012-2016. The 112 records that are included (552 in total) are from the years 2012-2015, as 2016 is not available. The spatial distribution of these records can be seen in Figure 4.

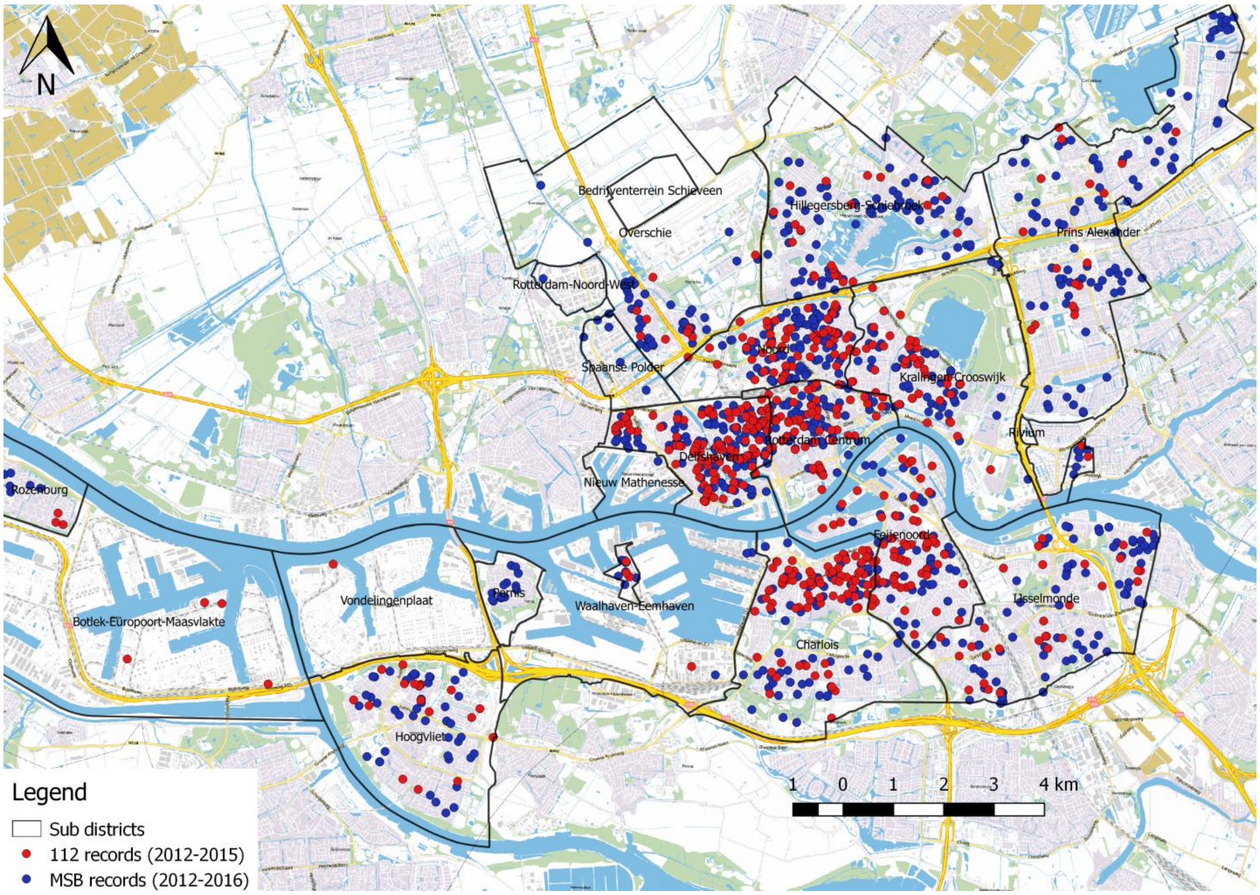

Figure 4: Flooding records (112 = emergency records, MSB= Municipality records) for the problem category 'Flooding in building'

It can be seen that most of the flooding in building records are situated in the 'Rotterdam Centrum', 'Delfshaven' and 'Noord' district. To check where the flooding incident density is highest and to identify potential hot spots, another heat map is created. The 112 records and emergency records are merged together for this analysis. The heat map, and the hot spots that are derived from the records, can be observed in Figure 5. For the determination of the hot spots, very small hot spots (<0,05 km^2) are again neglected from the investigation. It appears that there are clear hot spots with higher flooding density than the surrounding areas. In total, 18 hot spots are found. Similar to Figure 3, the largest hot spots are again situated in the sub districts 'Rotterdam Centrum', 'Delfshaven' and 'Noord'.

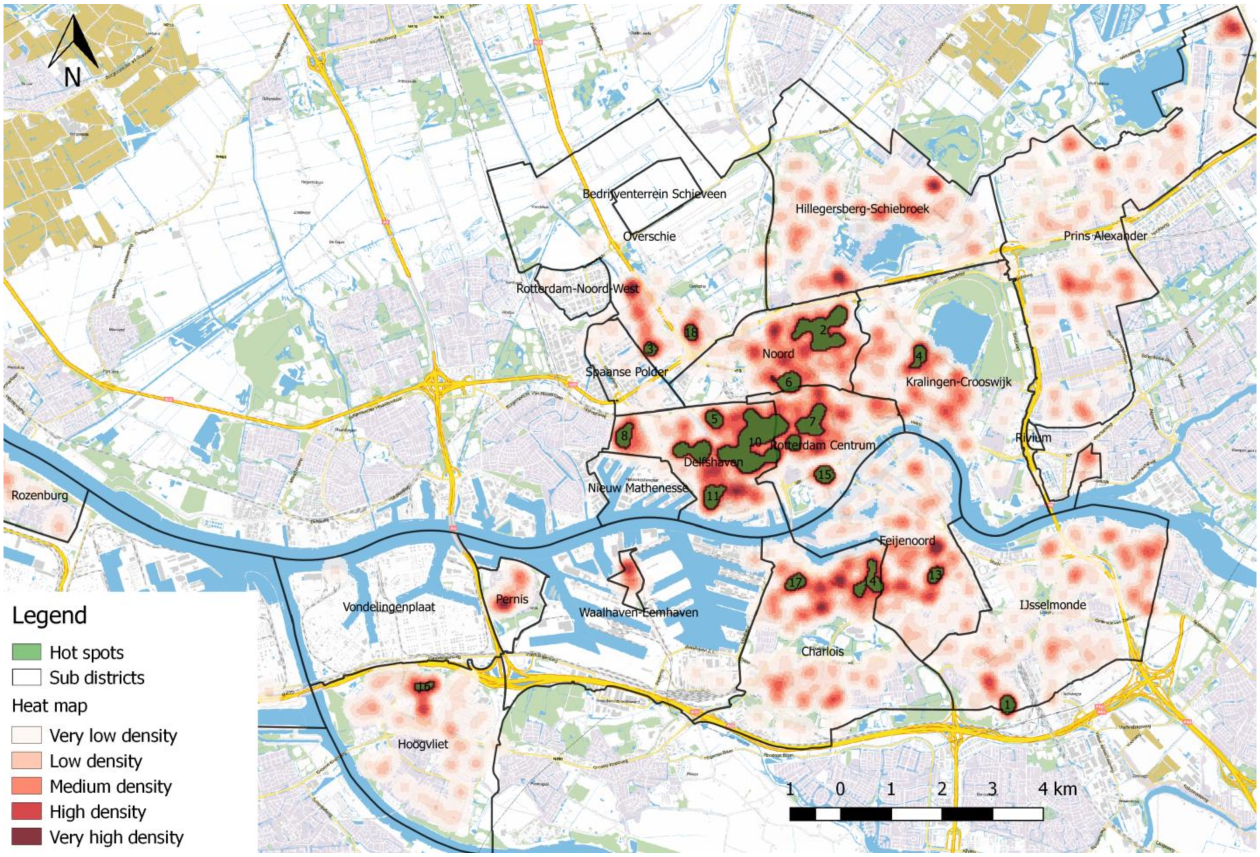

Figure 5: Heat map & hot spots for the problem category 'Flooding in building'

A spatial distribution of all flooding records has been created and hot spots in city are now identified, but not much more is known besides their locations yet. To be able to better explain where these flooding problems are related to, it is important to focus on the flooding incident statistics. These statistics can be used to learn about the contribution of different flooding incident types and perhaps about important failure mechanisms leading to the flooding incidents. The relative contribution of the different flooding incident types may give information about why there are certain hot spots in the city and what their failure mechanisms are. Also potential differences between hot spots can be mapped, based on the statistics. This will be further investigated in the following chapter.

Summary

In this chapter, flooding incidents have been plotted for the years 2012-2016. These flooding incidents are based on the call center data of the Municipality of Rotterdam. It is assumed this data can be used as a representable visualization of the actual flooding incidents in the city. A heat map has been created that shows flood prone hot spots. The biggest cluster of hot spots is found in the sub districts of 'Rotterdam Centrum', 'Delfshaven' and 'Noord'. A smaller cluster is found in the sub districts of 'Feijenoord' and 'Charlois'. A similar spatial analysis is performed, which focuses on the flooding incident category of 'flooding in building'. Besides call center data, also emergency call records are used for the analysis. A heat map reveals flood prone hot spots, which are quite similar to the hot spots based on all of the flooding records. The biggest flood prone locations are again in the sub districts of 'Rotterdam Centrum', 'Delfshaven' and 'Noord'.

2. Flooding incident statistics, failure mechanisms and hot spot origins

In this chapter, flooding incident statistics will be investigated, which can be used to learn about dominant failure mechanisms as well as the origin of the identified hot spots. In Table 2, the exact number of records before and after filtering can be observed. It also shows what percentage is left after filtering. It follows that only a small part (< 10%) of the original amount of records is discarded due to the lack of record information. The seven different categories (Table 1) that are used to categorize the filtered records show clear differences in quantities. The exact figures can be observed in Table 3 & 4 in Appendix A. These tables are used to create Figure 8 and 9.

Year	Original total amount of records	Total amount after filtering	Percentage of original set
2012	4527	4400	97,2
2013	4104	3834	93,5
2014	4243	4035	95,1
2015	5740	5476	95,4
2016	6284	5733	91,2

Table 2: Amount of handled records

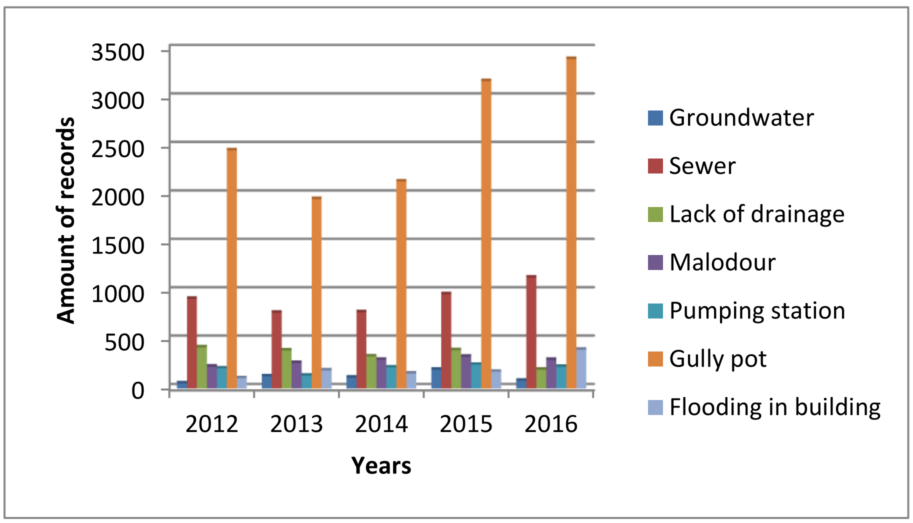

Figure 8: Distribution of records within the defined categories and years of data

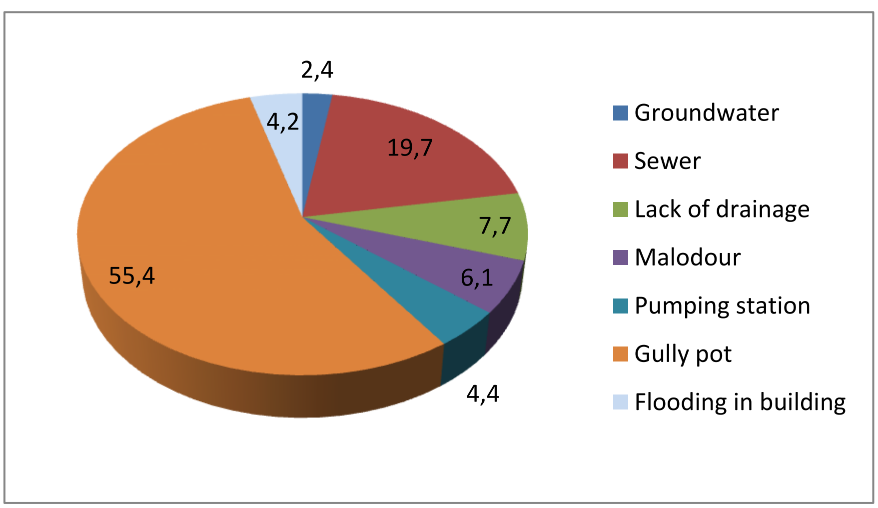

Figure 9: Relative contributions of defined categories throughout the different years of data (%)

From Figure 8 and 9 it can be clearly seen that most of the complaint calls are about problems related to gully pots. In most of the cases, these problems are about gully pot blockages and ponding of water on the streets as a result. The second highest amount of flooding incidents is related to sewer system problems. In general, these problems contain descriptions about sewer system blockages or dirty water on the surface. It is important to note that problems related to either gully pots or sewers can also be related to heavy rainfall, as system overload can lead to flooding on the streets. However, this correlation will be further investigated in the next chapter. After the clear domination of gully pot and sewer system related problems, there is a less pronounced order of category contributions. Lack of drainage was a relatively larger category before sorting. However, many of the records descriptions in this category were about gully pot or sewer blockages, which was not correct. The lack of drainage category should be related to water that cannot excess the sewers system due to a lack of access points, with ponding as a result. Therefore, all of these misfits were re-assigned in the filtering process of the raw unsorted data.

Now, to learn more about the properties and origins of the identified hot spots, the density of flooding records will be calculated as well as the contributions of the different flooding categories for each hot spot. First of all, the flooding record density is calculated for each hot spot. The importance of this is understanding how much flooding records are actually behind those hot spots. This is not yet known, as the created heat map (Figure 2) was a qualitative map. The calculation is done in GIS by a count of all records within the hotspot polygons, followed by a calculation of each polygon area. The output figure gives flooding record density per squared kilometer. The differences in densities can be observed in Figure 10 below.

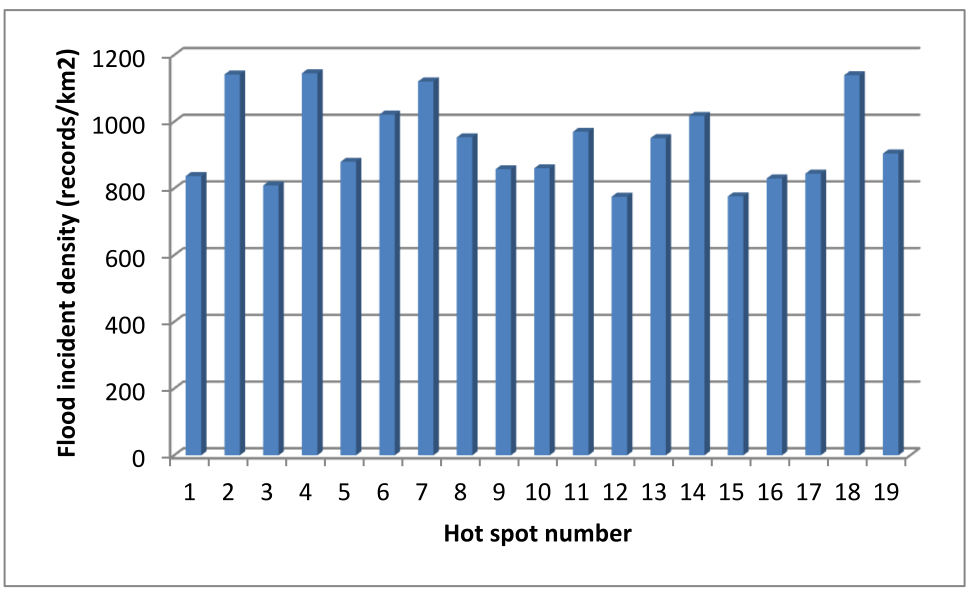

Figure 10: Hot spot flooding record densities

The hotspot densities range from 775 to 1145 records per squared kilometer (accumulated over 5 years' time). It can be observed that hotspot 2, 4, 7 and 18 have the highest record density. Apparently, the flooding probability is highest in these hot spots, assuming that the flooding records are a realistic representation of all of the actual flooding problems.

From the results shown in Figure 8 & 9, it follows that the gully pots are clearly responsible for the most flooding problems in the city of Rotterdam. However, whether this is also true or not for the flooding hot spots in the city might give information about the origin of the hot spot. Therefore, all of the reported flooding incident locations over the years 2012-2016 are clipped with each of the hot spot polygons. In this way, the flooding complaints forming the hot spots can be individually investigated to see if the problem categories have a different composition than the average composition of all flooding records. How this is performed, is visualized in Figure 11 in Appendix B. Subsequently, the flooding records are extracted from GIS and sorted in Excel. A chart is created from the flooding category composition for each hot spot. This chart is Figure 12, which can be observed below.

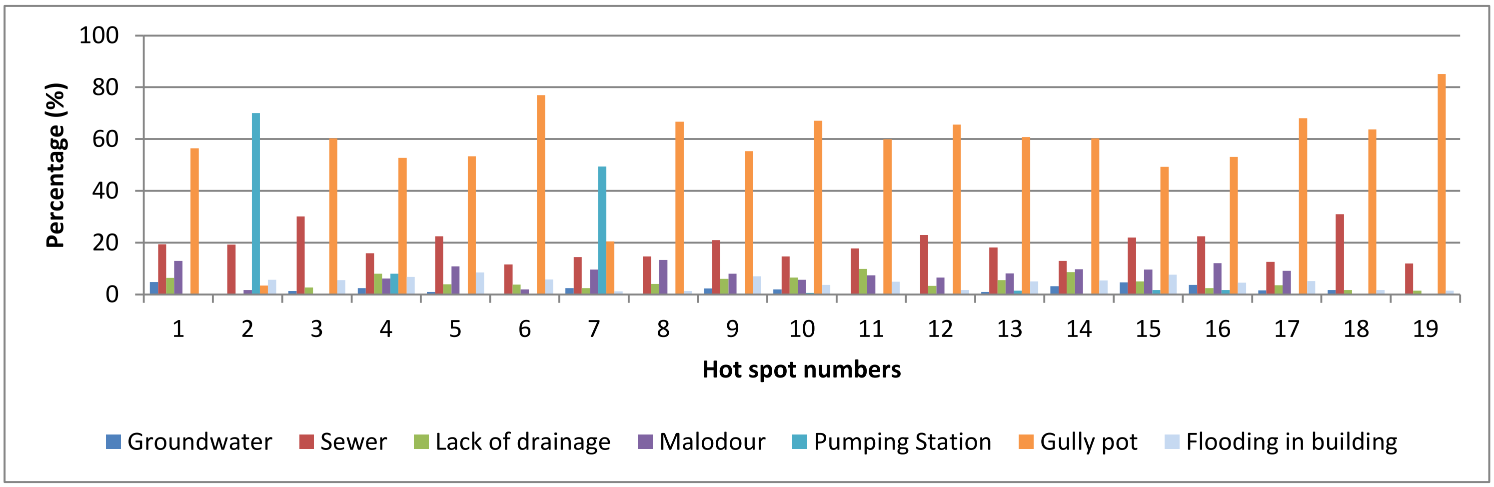

Figure 12: Flooding incident categories and their contributions to the different hot spots

It follows from this chart that most hot spots follow the average composition of flooding records, which means that the gully pot category forms the biggest problem, followed by the sewer category (Figure 8 & 9). However, there are a two outliers. Hot spots 2 & 7 show pumping station as the main problem category. This is interesting, as in the general composition of problem categories the pumping station category only has a small contribution. The gully pot category, which is the most dominant one for all hot spots except 2 & 7, consists almost only out of gully pot blockage related problems. This follows from the descriptions of the complaint call data. Therefore, the main failure mechanism is gully pot blockage for these hot spots. Another important failure mechanism is related to the sewer category, which is the second most dominant one. If the complaint category is sewer, than the failure mechanism behind this is almost always sewer pipe blockage. Flooding caused by the failure mechanism of sewer pipe overloading appears to be rare. This failure mechanism might also not be completely independent from sewer pipe blockage, since partial blockages accelerate sewer pipe overloading. These failure mechanisms can therefore be considered as interrelated. Anyhow, sewer pipe overloading is one of the subjects of interest in the investigation about the relation between rainfall and flooding on the streets. This relation will be investigated in next chapter. The results for hot spots 2 & 7 suggest that these areas can be considered flood prone mainly due to pumping station failures, making pumping station failure the main failure mechanism here. Analysis of the pumping station location shows that the dominance of pumping station disturbance in hot spot 2 and 7 is not strange, as there are a lot of small pumping stations in the direct proximity of hot spot 2 and 7 (Figure 13, Appendix B). Pumping station disturbances are therefore a proper explanation for the origin of these hot spots.

To find out what the origin of the other hot spots is, additional analyses need to be performed. For example, the amount of inhabitants might play a significant role in the amount of recorded flooding records. Also, the degree of imperviousness might be a dominant factor that increases the amount of flooding records. Therefore, the influence of population density and degree of imperviousness on the amount of flooding records will be investigated. First of all, Table 5 is created, which shows where the 19 hot spots are located and what type of area it is. The locations of the hot spots are represented by the postal code zones that contain the hot spots. Land type is residential area everywhere, except for hot spot 10, which is commercial area. Now, population statistics are under investigation. Population statistics for the Municipality of Rotterdam are retrieved from Centraal Bureau van de Statistiek (2013). Here, data is found that shows the amount of inhabitants per postal code zone in Municipality Rotterdam. This data is visualized in Figure 6 in Appendix B. The flooding record distribution is also visualized and can be seen in Figure 7 in Appendix B. Figure 6 and 7 can be compared to see what the relation is between the amount of inhabitants and the amount of complaint calls. It would seem logical to assume there is a positive correlation between the amount of inhabitants and amount of records. In other words, a high amount of inhabitants leads to a high amount of records. This can be investigated by creating a scatter plot showing amount of inhabitants versus amount of records. Each data point represents a different postal code zone. This image can be seen in Figure 14.

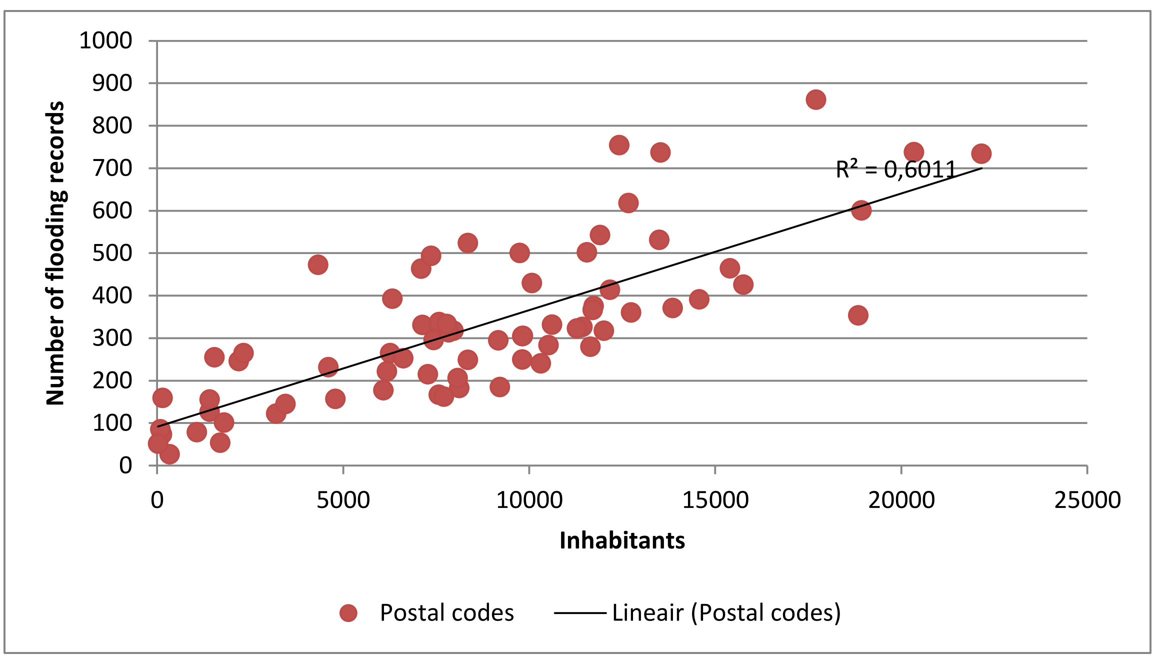

Figure 14: Correlation between amount of inhabitants and amount of flooding records

The expected relation between amount of inhabitants and amount of flooding records is confirmed by Figure 14, as there appears to be a positive correlation that is close to linear. In other words, a high amount of inhabitants will lead to a high amount of complaints and vice versa. It also becomes clear that residential area is the dominant land type where hot spots are located. This can probably be explained by the fact that in residential areas it is more likely that people will complain if there are water related problems, as it directly decreases their living quality. However, there is one exception and that is hot spot 10, which is located in the heart of the city center, making the land type commercial area (Figure 3). While the complaint call density is highest in this area, the amount of inhabitants varies per postal code zone. The amount of inhabitants might be high in postal code zone 3011, but it is very low in adjacent zone 3012. Therefore, for this zone, the correlation shown in Figure 14 does not hold. This can however be explained by the fact that the commercial center consists of lots of high economic value buildings or practices (work or shopping). Hence, lots of people visit the commercial center. All of those people experience the urban flooding problems, which increases the chance that these flooding incidents are captured in the call center data. Another outlier in Figure 14 is postal code zone 3071, that lies in the north of the Feijenoord district. While the amount of inhabitants is quite high, the amount of flooding records is quite low. A possible explanation for this is that a part of the area is industrial (locally few inhabitants), the area is a little bit less impervious than the city center and it is surrounded by open water (higher probability that water does not runoff to the sewer system).

The following potential factor that influences the origin of flooding hot spot is degree of imperviousness. The geo-database from the Municipality has a map available that provides information about land use in Rotterdam. This land use map can be used to calculate degree of imperviousness for all of the postal code zones. Afterwards, this information can be linked to the hot spots that are contained in the postal code zones. Seven different categories are handled in the land use map, which are: buildings, unpaved, paved, semi paved, water, infrastructure & remaining. Here, buildings can be correlated to rooftops, infrastructure to roads for vehicles or bicycles and the 'remaining' category to structures like tunnels or bridges. The unpaved category consists of green pervious surfaces like vegetation or lawns. Obviously, the 'water' category does not contribute to surface runoff, as this surface type represents open water bodies. It will therefore not be taken up in the degree of imperviousness calculation. The paved, semi paved and infrastructure category can be seen as one surface type, as they all consist of a combination of asphalt or brick pavement surfaces. The surface type for the 'remaining' category would be asphalt or concrete. Based on this information, the pervious and impervious surfaces can be factorized by runoff coefficients to correct for the fraction of surface runoff that does infiltrate. Various literary sources are used to find a correct range of runoff coefficients per surface type (Butler & Davies, 2004; California Water Boards, 2009; Cornell Engineering, 2008). According to the properties described above, appropriate figures from within the ranges are chosen as runoff coefficients (C). They can be seen in Table 6 below.

Land type category	Runoff coefficient (C)
(Semi) paved or infrastructure	0.80 (C_1)
Buildings	0.80 (C_1)
Unpaved	0.20 (C_2)
Remaining	0.90 (C_3)

Table 6: Runoff coefficients for the land types that (partially) contribute to surface runoff

The areas of all elements (≈570.000) of the land use map are calculated in QGIS. The equation that will be used to calculate the ratio of imperviousness can be seen in Formula 2:

$$\%\ Imperviousness = \frac{Area_{impervious}}{Area_{total}} \tag{2}$$

$$= \frac{\sum(Area_{semi\ paved;paved;infrastructure;buildings}) * C_1 + \sum(Area_{unpaved}) * C_2 + \sum(Area_{remaining}) * C_3}{\sum Area_{semi\ paved;paved;infrastructure;buildings;unpaved;remaining}}$$

With this equation, it is possible to calculate the degree of imperviousness for each postal code zone. The result of these calculations are displayed in Figure 15 (Appendix B), which shows the distribution of degree of imperviousness per postal code zone for the whole Municipality of Rotterdam. To investigate if a similar correlation like shown in Figure 14 can be found for imperviousness and amount of flooding records, a similar scatter plot is created. This can be seen in Figure 16 below.

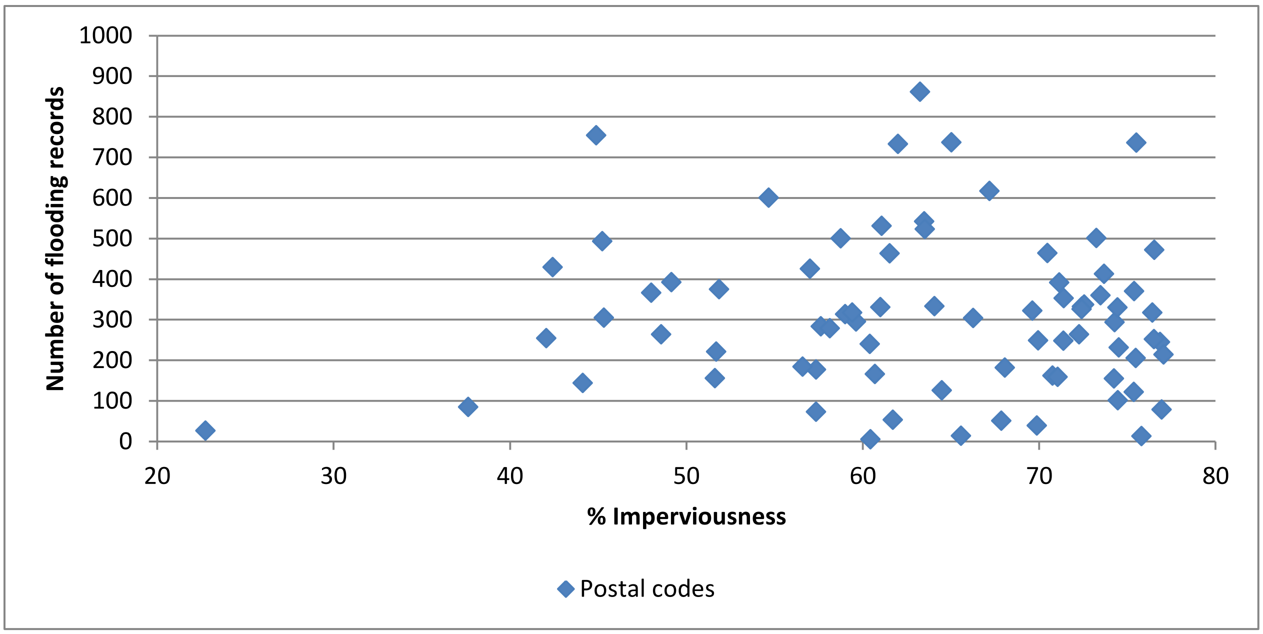

Figure 16: Degree of imperviousness versus number of flooding records

It follows from this scatterplot, which is based on data of all postal code zones, that no clear correlation between imperviousness and number of flooding incidents is found. The data points are spread out too much. It has already been made clear that amount of inhabitants influences the amount of flooding records. Amount of inhabitants is therefore a factor that distorts a potential relation between imperviousness and amount of complaint calls. An example of this is as follows. There are a couple of postal code zones that are industrial area (3044, Spaanse Polder; 3196, Vondelingenplaat etc.), which usually corresponds with a high degree of imperviousness, but none or only a few inhabitants live there. Therefore, there will not be a high number of complaints for these areas, but it does not necessarily mean that there are no flooding incidents there. To investigate whether there are more factors that affect the relation between imperviousness and amount of flooding records, a correlation matrix is created, which can be observed in Table 7. This table consists of correlation coefficients, in which 1 implies a perfect correlation. The closer the figure is to zero, the weaker the correlation. If the figure is negative, this means the relation between the two factors is reversed. If one factors grows, the other shrinks.

	Inhabitants	No. of records	Area	Imperviousness
Inhabitants	1	0,78	0,056	0,10
No. of records	0,78	1	0,25	0,025
Area	0,056	0,25	1	-0,67
Imperviousness	0,10	0,025	-0,67	1

Table 7: Correlation matrix of amount of inhabitants, number of records, area & imperviousness

It follows from Table 7 that the previously found and explained correlation between amount of inhabitants and number of records is confirmed (correlation factor of 0.78). Since number of records is affected by amount of inhabitants, the relation between imperviousness and amount of flooding records is distorted. It also follows that apparently area has a reversed correlation with imperviousness (correlation factor of -0,67), which means that if area size decreases, imperviousness tends to grow larger. This relation can be seen in Figure 17.

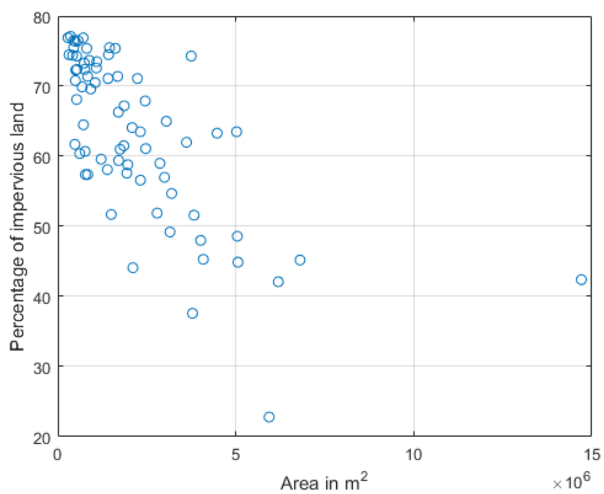

Figure 17: Correlation between area size of postal code zones and degree of imperviousness

This phenomenon can be explained by the fact that the postal code zones in and around the city center district are relatively small, but very impervious. Since imperviousness and number of flooding records are both influenced by other factors, no correlation follows from the scatterplot in Figure 16. Therefore, perhaps a better way to investigate the influence of imperviousness on flooding incidents is by comparing it with the location of the flooding incident hot spots as shown in Figure 3.

Figure 18 shows an overlay of the flooding hot spots (based on all record data from 2012-2016) and the map of imperviousness. It is striking to see that the biggest and most hotspots are located in the zones that have the highest class of imperviousness, which are the sub districts of Rotterdam Centrum, Noord and Delfshaven. Also a couple of hot spots are situated in the highest impervious areas of sub districts

Feijenoord and Charlois. From this it can be concluded that degree of imperviousness does affect the amount of flooding incidents, as the biggest and most flooding incident hot spots are enclosed by the highest impervious zones. The same relation holds for the flooding in building hot spots (Figure 5), which have similar locations as the hot spots shown above (based on all data from 2012-2016).

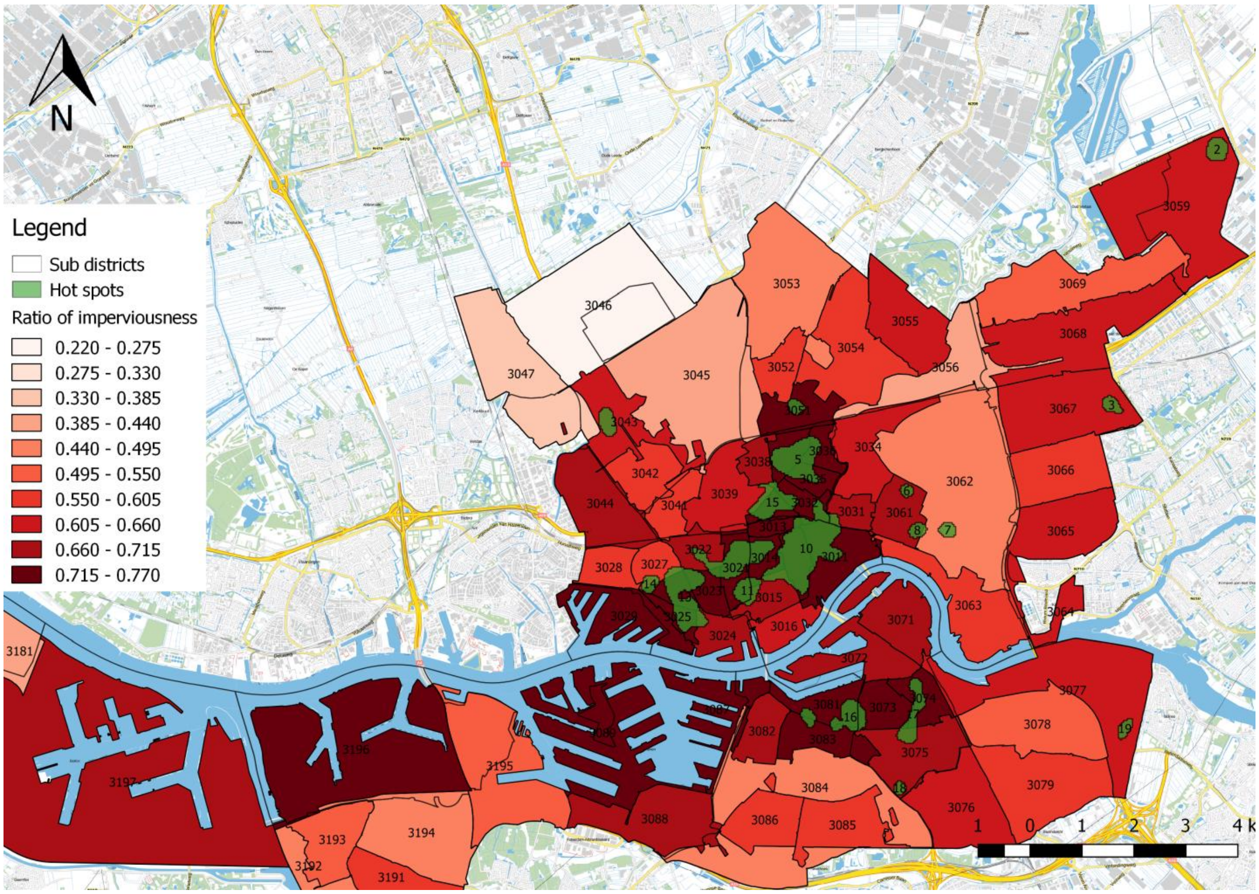

Figure 18: Map of imperviousness per postal code zone versus hot spot locations

Summary

Based on the different problem categories in the Municipal call center data, the contribution of each problem category has been calculated over the years 2012-2016. It follows that flooding problems related to gully pots are the most dominant problem in the Municipality of Rotterdam (≈55%), followed by sewer related problems (≈20%). The most dominant failure mechanism leading to flooding incidents appears to be gully pot blockage, followed by sewer pipe blockage. Subsequently, an investigation about the problem category contributions for each flooding hot spot (based on the five years of data) has been performed. All hot spots have the same pattern as the average contributions over the years 2012-2016, except for hot spot 2 & 7. The origin of hot spots 2 & 7 can be found in pumping stations disturbance, according to the problem category contributions. To investigate the origin of the other hot spots, amount of inhabitants and degree of imperviousness have been investigated versus amount of complaint records. It follows that there is a positive and quite linear relation between the amount of inhabitants and the amount of complaint calls. At the most dominant hot spot locations however, population density is not at its highest, validating that at these hot spots actually originate out of flood vulnerability. While the relation between imperviousness and amount of complaint calls is less pronounced, there is a clear relation between the dominant flooding incident hot spots and imperviousness. The most dominant hot spots are located within the zones of highest imperviousness, from which it can be concluded that imperviousness does have a substantial influence on the location of flooding incidents.

3. Influence of rainfall on flooding incidents

In the previous chapters, the total amount of reported flooding incidents from 2012 to 2016 have been investigated. This investigation, based on the spatial distribution of the flooding incidents, has led to the identification of a set of hot spots where the probability of urban flooding is higher. Also, a review of the statistics of 2012-2016 flooding record data set has shown that gully pots have a dominant role in the occurrence of urban flooding. The main sewer system also plays a significant role. The question arises whether urban flooding is mainly caused by failure of these assets or by external factors. As discussed earlier, urban flooding can be caused by both natural and human factors (Tingsanchali, 2011; ten Veldhuis et al., 2011). Human factors can be related to maintenance issues, causing gully pot or sewer system blockages, leading to urban flooding. Natural factors can be related to rainfall. To better define what is considered heavy rainfall, the definitions of the KNMI can be used. They consider 50mm of rainfall in 24 hours extreme rainfall. A cloudburst is defined as 10mm rainfall in 5 minutes or 25mm rainfall in 1 hour (Notitie extreme neerslag in Rotterdam, 2016). These type of rainfall events in Rotterdam are interesting to investigate.

In this chapter, the relative influence of rainfall on urban flooding incidents will be investigated. Since this research focuses on retrieving vital information from call center data, this is again the approach to find out what the relative influence of rainfall is on urban flooding incidents. This will be done in a stepwise approach. Throughout the years of 2012-2016 a number of dry days, light to medium rainfall days and heavy rainfall days will be selected. Subsequently, the amount of received water related complaint calls will be investigated on those days. The purpose of investigating the amount of flooding records on dry days is creating a baseline of flooding incidents that occur independent of the influence of rainfall. This can then be taken into account when investigating the amount of recorded flooding incidents during light and heavy rainfall event days. From the present complaint call categories (Table 1), only a few can be directly related to rainfall. 'Malodour' and 'pumping station' (disturbance) are not affected by rainfall. The relation with groundwater is more complex. A singular heavy rainfall event will not have much effect on the groundwater head, but this is different if it has been raining the whole month. To know what the exact relation between groundwater heads and rainfall is, groundwater heads over time should be investigated, but that is outside of the scope of this thesis. Besides this, groundwater related problems only on average take up 2,4% (Table 5) of the reported flooding incidents. Therefore it is neglected from the research about the relation between rainfall and flooding incidents. The categories that can be affected by rainfall are 'flooding in building', 'gully pot', 'sewer' and 'lack of drainage'.

From the results of the investigation, it should be possible to address the relation between rainfall and recorded flooding incidents. If this is true, then it might also be possible to identify vulnerable hot spots, which appear to be extra susceptible to the influence of rainfall, based on a higher spatial density of recorded flooding incidents. The spatial distribution of flooding records during heavy rainfall events will also be coupled to the spatial distribution of rainfall during the events. This will be visualized in GIS software to see if it can be used to explain potential vulnerable hot spots based on the call center data. The theory behind this is that rainfall events can be highly spatial inhomogeneous. Therefore, it might be possible that the locations that endured that heaviest rainfall can be connected to flooding incident hot spot locations. To get a general idea of what the rainfall behavior is in the Municipality of Rotterdam, a rainfall intensity frequency curve is drawn, averaged over the 5 years of historical data. This can be seen in Figure 19 below.

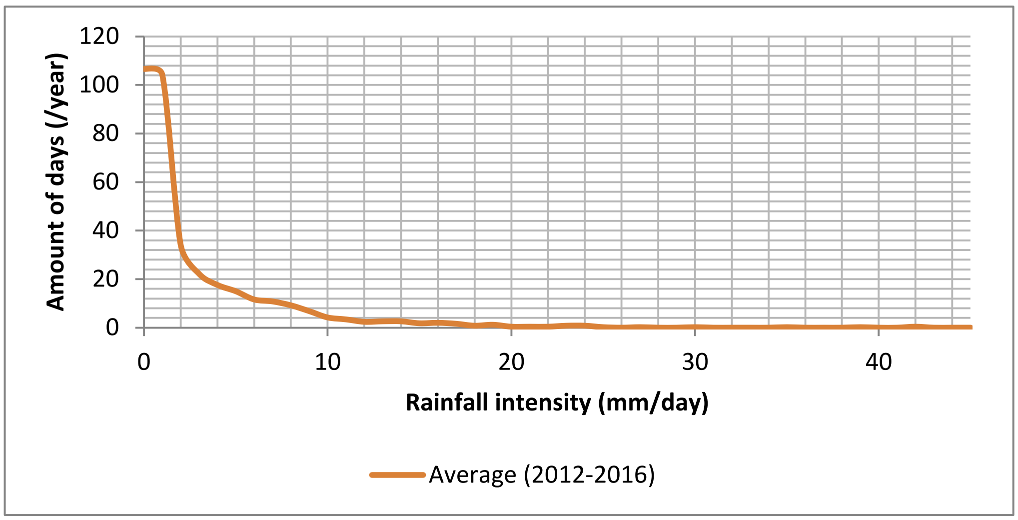

Figure 19: Rainfall intensity frequency curve

To start with the stepwise approach, first a couple of dry days will be selected to set a baseline of complaint calls that are received independent of rainfall. A total of 10 dry day events will be selected within the range of the years 2012 – 2016. For the light rainfall events, 5 events of around 5mm rain per 24 hours are considered. The total amount of rainfall per day is measured by rainfall stations: Rotterdam Airport, Hoek van Holland, Pernis and Rozenburg, which are all situated in Municipality Rotterdam. The average value of these rainfall stations is taken as a measure for the total amount of rainfall in 24 hours. For the heavy rainfall events, 4 events are taken into account. According to Notitie extreme neerslag in Rotterdam (2016) there was one extreme rainfall event in 2013 and two cloudbursts, one in 2012 and one in 2016. Data from rain stations Rotterdam Airport, Hoek van Holland and Geulhaven is used for the extreme rainfall event of 13 October 2013. At 23 June 2016 there was also major rainfall event in which hospitals in Rotterdam were flooded and a substantial amount of damage was done. Data from rain stations Poortugaal, Rotterdam Airport and Hoek van Holland is used for this event. It is also taken up in the heavy rainfall category. Information about these events is summarized in Table 8 in Appendix A.

The flooding records of the 10 dry days are investigated for the categories ‘flooding in building’, ‘gully pot’, ‘sewer’ and ‘lack of drainage’. The sum of the complaints for each category is found over a period of 10 days. To find a baseline for the amount of complaints that come in on a single day or a 24 hours’ time period, these sums are divided by 10. Table 9 shows the result, the type and amount of complaints which can be expected independent of rainfall. It follows that on average 3 gully pot and 3 sewer related complaints will be recorded for a dry day. That sums up to an average of 6 flooding records per dry day.

	Gully pot	Sewer	Flooding in building	Lack of drainage	Total records
Records (/10 days)	32	29	3	4	68
Records (/ day)	3	3	0	0	6

Table 9: Expected type and amount of complaints on a dry day

Next, the flooding records for the 5 mild rainfall events of ±5mm/24 hours are investigated. The results are shown in Table 10 below. The amount of flooding records received on a dry day can be compared with the flooding records from a day with a light rainfall event. The time span in which flooding records are linked to a certain light rainfall event are therefore again 24 hours. For example, if a certain day has an accumulated rainfall amount of 5mm in a day, then all flooding complaint records of that day will be taken into account. Since it is known what the amount of complaint calls received on a dry day is, higher amount of complaint calls on light rainfall days can therefore be linked to the influence of rainfall. It can be seen in Table 10 that the amount of records with light rainfall events is 15, averaged over 5 different days. Although this difference between dry and light rainfall days is not very significant, the figure for complaints on light rainfall days is higher. That suggests that rainfall does increase the amount of flooding incidents. However, light rainfall shouldn’t be able to cause overloading of the urban sewer system as it is designed to drain these low intensities easily. Therefore, it is more likely that the increase of recorded flooding incidents is caused by human factors, like maintenance issues. Blockages of gully pots or sewer pipes mean a reduced drainage capacity, which, in combination with rainfall, could have ponding of water on the streets as a consequence.

	Gully pot	Sewer	Flooding in building	Lack of drainage	Total records
Records (/5 days)	50	18	2	6	76
Records (/ day)	10	4	0	1	15

Table 10: Expected type and amount of complaints on a mild rainy day

Now the focus will be on the received flooding records on days of heavy rainfall events. Since these heavy rainfall events vary in intensity and duration, they will be investigated separately. The following flooding incident records were captured for the different events (Table 11).

Event no	Date	Gully pot	Sewer	Flooding in building	Lack of drainage	Total records
16	11-6-2012	11	2	2	11	26
17	13-10-2013	43	29	48	13	133
18	4-6-2016	27	12	0	0	39
19	23-6-2016	269	97	125	33	524

Table 11: Recorded flooding incidents of the heavy rainfall incidents

As briefly mentioned, two of these events were caused by cloudbursts. These events are number 16 and 18. Event 16 occurred at 11-6-2012 and had an intensity of 25mm in an hour. Event 18 occurred at 4-6-2016 and had an intensity of 31mm in 40 minutes. From the comparison of event 16 and 18, it follows that event 18 was heavier, as there was a more intense burst of rain in a shorter time window. With event 18 being a heavier event, also the impact appears to be larger, as the amount of reported flooding incidents is higher for event 18. The rainfall events 17 and 19 both have a duration of 24 hours. Event 17, which happened on 13-10-2013, had an intensity of 59mm per 24 hours, which can be considered extreme rainfall. Event 19, which happened on 23-6-2016, had an intensity of 47mm per 24 hours. Both events clearly show higher amount of recorded incidents than for the cloudburst events 16 and 18.

The results above suggest that Rotterdam's drainage system is better capable at handling short heavy bursts of rainfall than consecutive hours of rainfall. A possible explanation for this is the peak time of Rotterdam's drainage system. As a rule of thumb, the time before the peak discharge has been reached in the sewer system is considered to be around an hour. This is generally a larger time period than the duration of a cloudburst. Therefore, not all water is able to access the sewer system before the cloudburst is already over. As a result, the sewer system should be able to drain the storm water before overloading occurs, assuming its assets function properly. With the extreme rainfall events, it is a different story. Since the duration of these events is at least 24 hours, the sewer system keeps filling up continuously, long after the peak flow has already been reached. Therefore, if the system's capacity is not sufficient enough, the system overloads with urban flooding as result. This clearly happened during events 17 and 19, as remarkable total amounts of flooding complaints were received that day.

Interestingly, while event 17 had a higher intensity (at least 10mm more rain), the amount of complaints that the Municipality received is about 4 times less. As mentioned, this can perhaps be explained by the spatial inhomogeneity of heavy rain events. There can be large local differences in rain intensities, potentially leading to lots of problems in one specific district, while surrounding districts encounter more moderate intensities. This follows for example from the different rain station measurements where the intensity of rainfall event 19 is based on. The 47mm (accumulated in 24 hours) is an average of the measured intensities of 49mm at Rotterdam Airport, 57mm at Hoek van Holland and 36mm at Poortugaal. Another explanation for the difference in complaint records for event 17 & 19 can be found in the rainfall intensity distribution over time. This distribution is visualized for both events and can be seen in Figure 20, Appendix B. A cumulative graph (Figure 21) for both rainfall events has been created to clarify the different impacts and hence different amount of flooding records. It follows that almost all rainfall (≈90%) of event 19 is concentrated between 01:00 AM-06:00 AM and its peaks are up to 3 times larger than those of event 17. This means that the urban drainage system had to coop with around 40mm of rain in only 5 hours' time, which had a big impact on the city and loads of flooding incidents as a result. For event 17, the rainfall is more spread out over the day and the intensities are lower. Also, it can be observed that there is a dry period of quite some hours in the middle of the rainfall event. This gives the urban drainage system time to drain away water that is both on the streets and in the system itself. The probability of system overloading and flooding incidents as a consequence is therefore reduced. This is the reason why there were fewer flooding complaints for event 17 than event 19, while event 17 carried more rainfall.

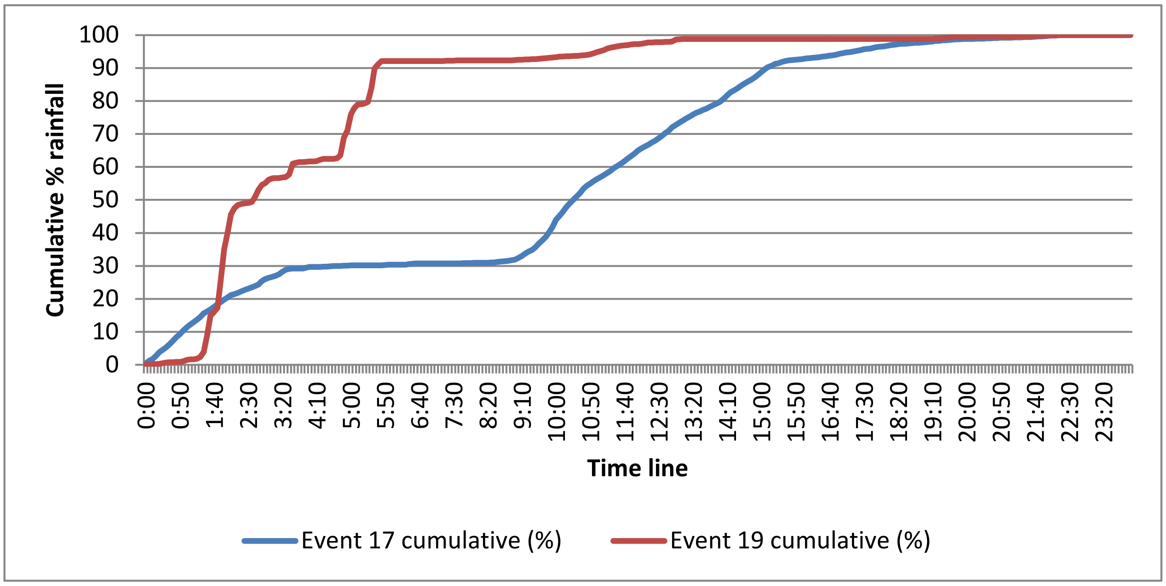

Figure 21: Cumulative percentages of rainfall for event 17 & 19

To make the correlation between flooding incidents and rainfall clearer, all of the defined events with a duration of 24h will be plotted against the amount of complaints calls. Additionally, extra rainfall events (from within 2012-2016) are added to the plot to increase the accuracy of the correlation analysis. These events vary from ±10 to ±25 mm in 24 hours, filling up the data gap in the plot. Since extreme rainfall events are rare, historic data is used on five more of these events ranging from 2005 to 2011 (Notitie extreme neerslag in Rotterdam, 2016). Information about these events can be found in Table 12. In total, 40 rainfall events are plotted as data points in a scatterplot of rainfall intensity (mm/24h) versus the amount of flooding records. This plot can be seen in Figure 22.

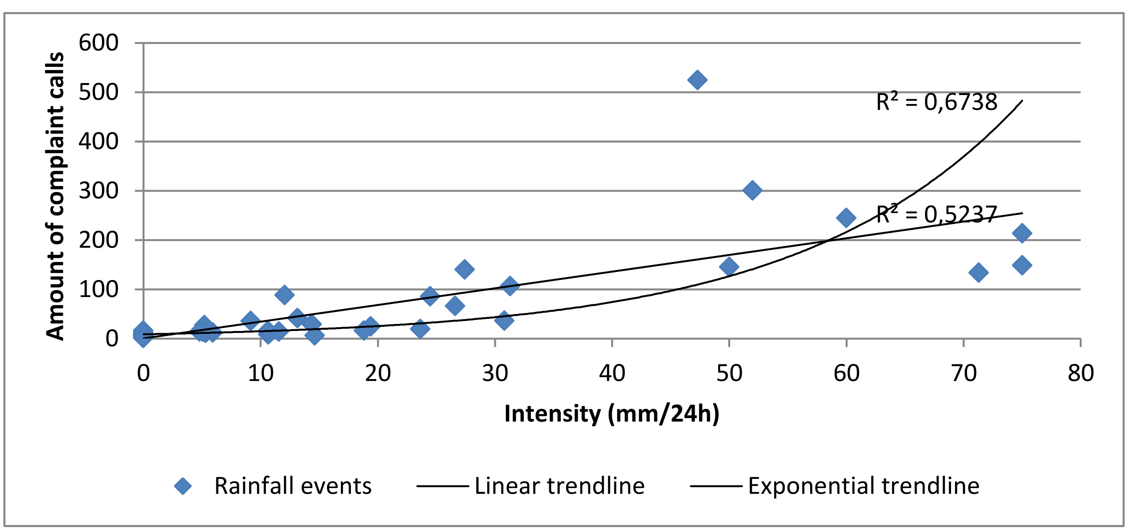

Figure 22: Influence of rainfall on amount of complaint calls

It follows from the investigation above that rainfall definitely has an influence on flooding incidents reports. However, this influence is not very strong at light rainfall conditions. The influence actually gets stronger if rainfall intensities become higher. This can already be derived from the data of Tables 8, 9 & 10 in this chapter, but Figure 22 helps to visualize it. In the graph, the rainfall event data points can be seen as well as two trend lines, one linear and one exponential. The closer 'R' is to 1, the stronger the implied relationship. It can be observed that the exponential trend line is a better fit than the linear trend line. The exponential relation is also more logical, since the sewer system can store and drain quite some millimeters of rainfall without any problems. However, a moment can be reached that neither storage in the sewer system nor on the streets is possible anymore. At that moment, the amount of flooding complaints rises intensely, as urban flooding events are very likely to cause nuisance once the system is full. Therefore, the relation of rainfall on the urban drainage system can be expressed as exponential.

Since the influence of rainfall is strongest for heavy rainfall events 17 & 19, these will be further investigated in GIS to see if there are potential vulnerable hot spots in the city. Since extreme rainfall conditions can cause a lot of damage or dangerous situations, civilians that encounter these situations are likely to call the emergency number (112) instead of filing a complaint to the Municipality. Therefore, in the analysis of event 17 & 19 also the emergency records will be taken into account. Event 17 was responsible for 112 flooding related emergency call records, which have all been correctly geocoded. Event 19 was responsible for 66 flooding related emergency call records, which have all been correctly geocoded too. The spatial distribution of the flooding records for event 17 & 19 can be seen in Figure 23 & 24 (Appendix B). Based on these distributions, two new heat maps are created, which should give insight in the presence of hot spots. These hot spots appear to be extra vulnerable to flooding incidents, as most of the records are situated in these areas. The two new heat maps for event 17 & 19 can be found in Figure 25 & 26 (Appendix B). Taking into account the top ten percentage of highest density locations in identifying hot spots for both events, Figure 27 is created.

For event 17, the largest contribution of problem locations is situated in the sub district of Delfshaven. Event 19 shows the largest hot spots in the sub districts of Delfshaven, Noord and Rotterdam Centrum. Figure 27 actually shows a lot of similarities with Figure 3. Lots of hotspots from Figure 27 correspond with the hot spot locations that are based on all of the flooding records from 2012 to 2016 (Figure 3). This confirms that the identified hot spots in Figure 27 are indeed flood prone locations. Since the locations of the hot spots from Figure 3 & 27 correspond, it means that the heavy rainfall related hot spots are situated in the highest impervious areas too. Therefore, it is again confirmed that degree of imperviousness plays a role in the positioning of flood prone locations.

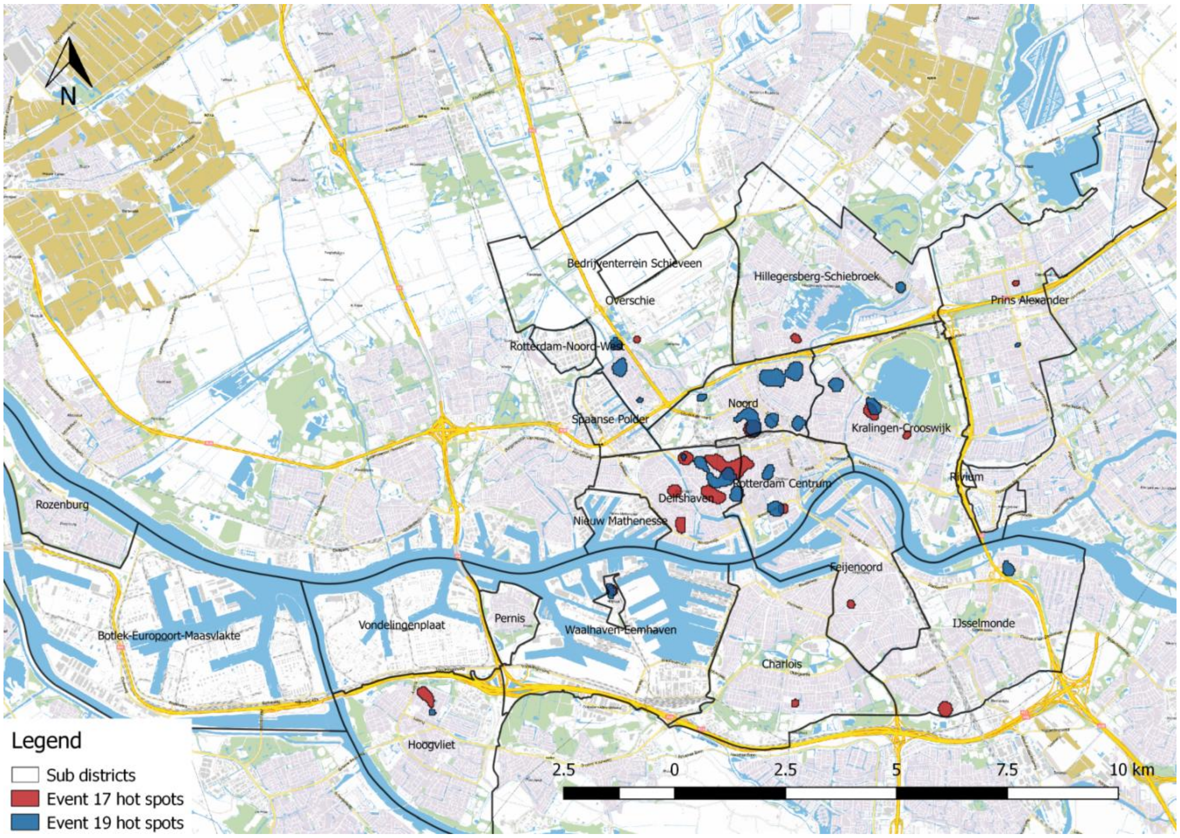

Figure 27: Hot spot map for heavy rainfall event 17 & 19

Statistics, intensity distribution through time and vulnerable hot spots based on events 17 & 19 are now known, but nothing is known yet about the intensity distribution through space. To find out more about this, 5 minute National Rainfall Radar images are used. All of these 5 minute images are aggregated to find a cumulative image of the rainfall event based on the 24 hour duration of the calendar day of the event. The image that is created for event 17 (13-10-2013) can be seen in Figure 28.

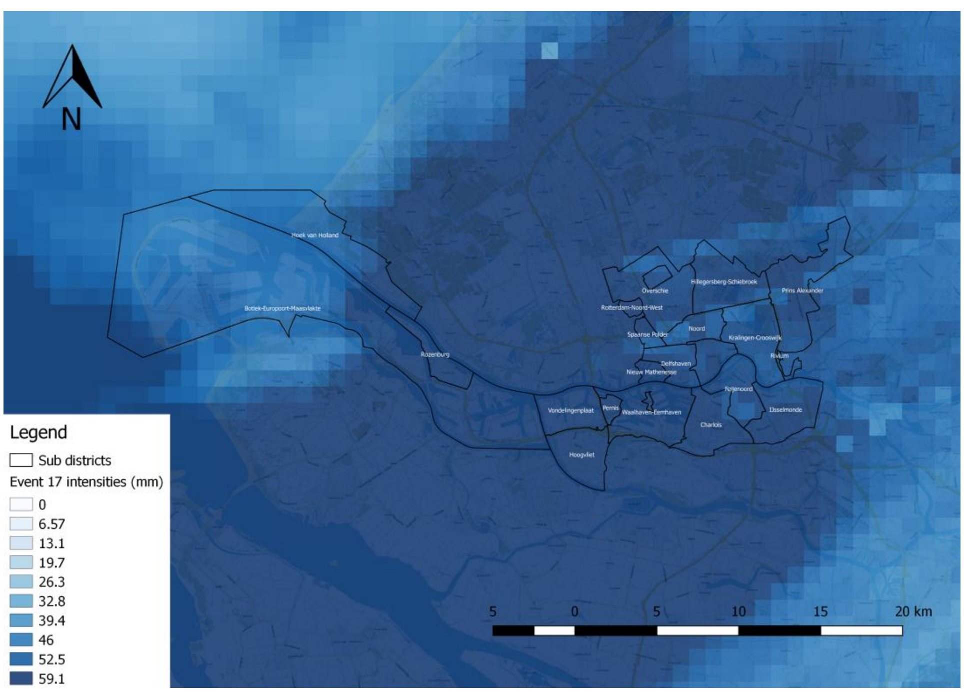

Figure 28: Rainfall intensity distribution through space aggregated over 24 hours (event 17)

Through Figure 20 it became clear that rainfall event 17 was quite spread out over time without large peaks. These characteristics corresponds with frontal rainfall caused by a warm front, which has the typical behavior of long periods of rainfall with low intensity on a large scale. This behavior is recognized when going through the 5 minute rainfall images throughout the 24 hour time interval of event 17. Therefore it is no surprise to see that the spatial distribution of rainfall (Figure 28) shows no large differences within the Municipality of Rotterdam. Since the most significant flooding hot spots are situated in the city center, a closer look at this area might give more information about the origin of the hot spots. This can be observed in Figure 29.

Figure 29: Rainfall intensity distribution around city center and hot spot locations (event 17)

Figure 29 shows that there are some differences in rainfall in and around the city center, but these differences are restricted to a few millimeters over a 24 hour period. In other words, for this rainfall event, the rainfall intensity differences in the city are quite negligible. This makes it difficult to make a connection between spatial rainfall intensity distribution and hot spot locations for this event. For an event with more intense rainfall peaks and larger local differences like event 19, this might not be the case. Large local differences in rainfall intensities might lead to a more dominant presence of flooding hot spots in the areas of high intensities. However, the resolution of 1x1km grids might be too inaccurate to make precise distinctions between hot spot origins on a sub district scale. The same analysis is performed for event 19 to investigate if a more concentrated rainfall event with higher peaks causes larger local rainfall intensity differences. Figure 30 shows the rainfall event for the whole Municipality of Rotterdam. Figure 31 shows a zoomed in image of the city center, which is used to check for local differences and to see if a connection can be made with the flooding record hot spots caused by this event.

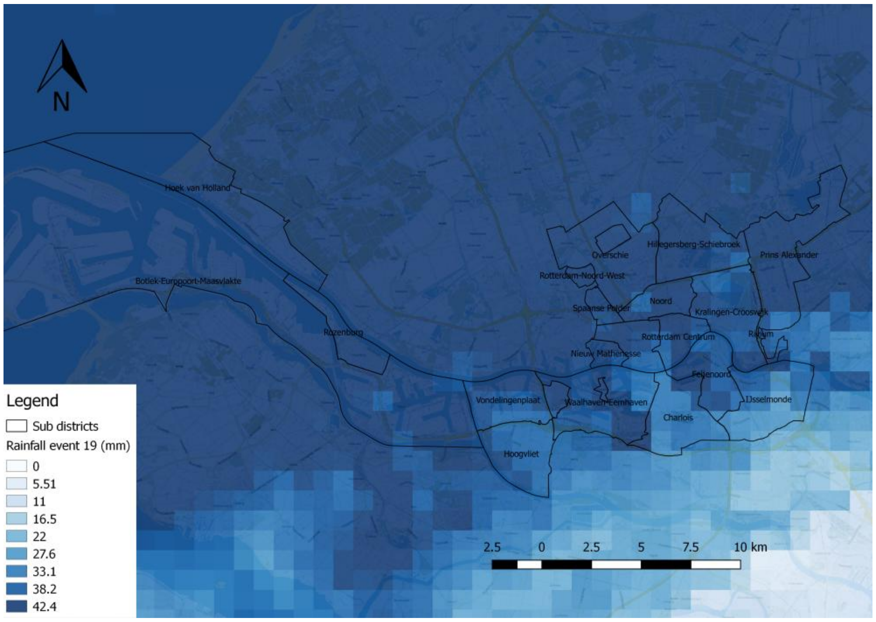

Figure 30: Rainfall intensity distribution through space aggregated over 24 hours (event 19)

It follows from Figure 30 that the south-east of Rotterdam clearly had less rain than the other parts of the Municipality. This causes some local rainfall intensity differences around the city center area. Figure 31 below shows these local rainfall intensity differences more clearly. The darkest purple layer displays the heaviest rainfall intensities (99-100% of maximum intensity), followed by a lighter purple layer (95-99%), a dark blue layer (90-95%) and a lighter blue layer (85-90%). The remaining intensities are shown by the rainfall intensity raster layer, which can also be seen above. As expected, for event 19, the local rainfall intensity differences are more pronounced then event 17. This can for example be seen in the sub districts of Delfshaven, Rotterdam Centrum, Kralingen-Crooswijk & Noord, where there are local differences of up to 6.5 mm for adjacent (1x1km) grid cells. Although there are clear intensity differences for this event, it still is quite difficult to make a direct connection between the hot spot locations and the highest intensity areas. Not all hot spots are situated in the highest intensity areas and as mentioned earlier, the grid cell resolution is quite course. Therefore, it follows from this investigation that no direct link can be made between highest intensity rainfall areas and flooding hot spot locations. At least, not with this resolution of rainfall data.

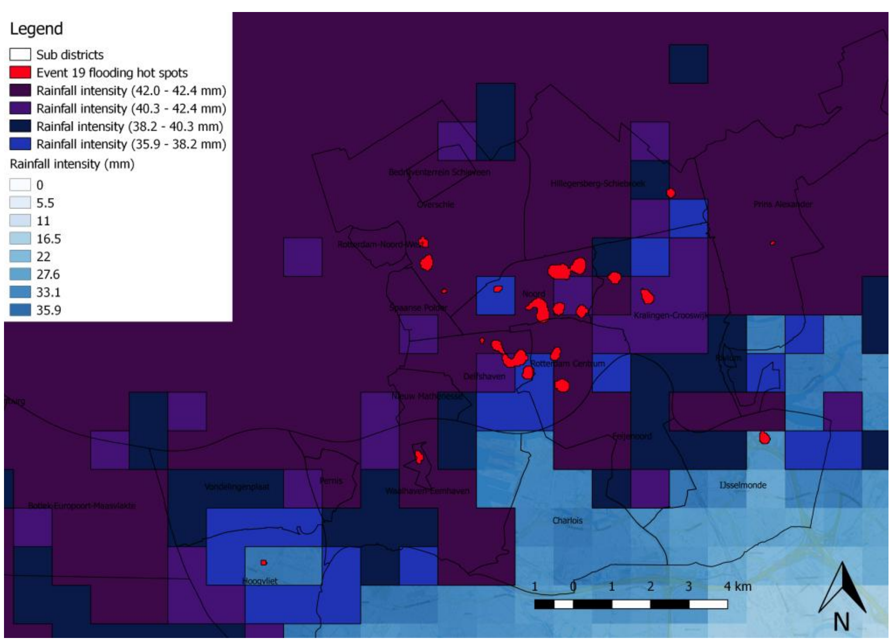

Figure 31: Rainfall intensity distribution around city center and hot spot locations (event 19)

Summary

The influence of rainfall on flooding incidents has been investigated in this chapter. This is performed by plotting different rainfall event intensities versus the amount of flooding records. From this, it can be concluded that there is an exponential relation between rainfall and flooding incidents. In other words, weak rainfall conditions do not lead to much flooding incidents, whereas heavy rainfall conditions lead to very high amounts of flooding incidents. By comparing differences in resulting flooding records for heavy/extreme rainfall events and cloudbursts, it follows that Rotterdam's drainage system is better capable at handling short heavy bursts of rainfall than very long periods of rainfall. It has also been analyzed how the structure of a heavy/extreme rainfall event influences the response of the urban drainage system. Finally, a new heat map is created based on rainfall event 17 & 19 showing vulnerable flooding hot spots that correspond with the previously found flood prone locations. A spatial rainfall intensity distribution of event 17 & 19 appeared to be unsuitable to make the connection with flooding hot spot locations, as the highest rainfall intensity pixels did not correspond everywhere with hot spot locations. Also, the coarse resolution (1x1 km) of the National Rainfall Radar reduces the ability to make such a connection.

4. Influence of seasonality on flooding incidents

Thus far, flood prone areas in the Municipality of Rotterdam have been identified. The statistics of the flooding records have pointed out that gully pot related problems are responsible for most flooding incidents in Rotterdam (≈55%). Based on the descriptions of the gully pot flooding records, it turned out that gully pot blockage is the dominant failure mechanism. It has also been proven that heavy rainfall increases the amount of flooding incidents, in which the gully pot problem category again plays a dominant role. However, it has not yet been accomplished to be able to separate between human factors (lack of maintenance issues causing gully pot blockages) and natural factors (heavy rainfall) causing flooding incidents. Enhanced knowledge about this is valuable for the improvement of asset management strategies in order to reduce the amount of flooding incidents. An example will be given, that can also be observed in Figure 32. It is possible that sewer or gully pot flooding related records get mixed up, as both problem categories can lead to flooding on the streets. However, the driving factors and failure mechanisms behind this are different. If the driving factor behind the flooding problems is human, then the cause of the problems will mainly be related to the failure mechanism of gully pot blockages and flooding on the streets as a result. If the driving factor is purely natural (heavy rainfall), than sewer system overloading will be the main failure mechanism leading to flooding on the streets.

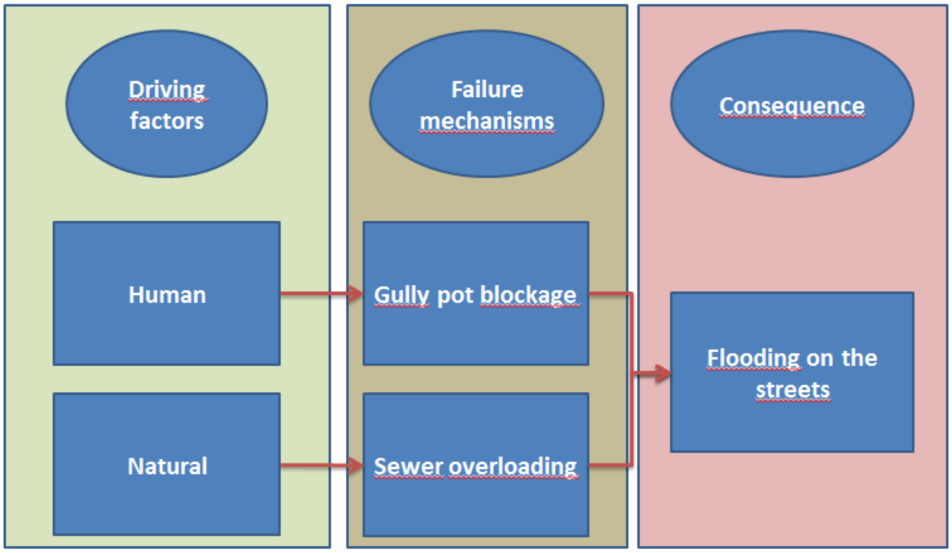

Figure 32: Flow chart of human and natural factors leading to flooding on the streets

To be able to distinguish between the driving factors behind these type of urban flooding events, the influence of seasonality on flooding records will be investigated. The focus will be purely on the gully pot related flooding records. The idea behind this is that gully pot blockages are mainly susceptible to leaves falling from trees and ending up in gully pots. The presence of leaves on trees (or on the ground) in the Netherlands can mainly be expected in the period of April to December. Therefore, perhaps a seasonal pattern can be observed that gully pot blockages are more present in this time period. Especially in the time period of Summer to Autumn (Juli – October). If such a pattern exists, a link can also be made with the amount of trees in certain areas of Rotterdam. Areas that will be checked for the presence of trees are the previously found flood prone hot spots. This can be used to confirm the influence of seasonality on flooding incidents, as tree leaves play a big role in effects of seasonality.

To start the analysis, first of all, the gully pot records for the years 2012 to 2016 are clipped with the hot spot layer. Hot spot 2 & 7 are neglected from the investigation, as their origin is identified to be pumping station related. Now, for the remaining hot spots the amount of gully pot records is known. The amount of records for each hot spot can be found in Table 13. Subsequently, the gully pot records of all hot spots are summed and grouped per month. The records are summed, because some hot spots do not have much records, which means there would not be large monthly differences. Therefore it would be quite difficult to derive correlations. The monthly variance in received gully pot records follows from summing and grouping the records per month. The results can be seen in Figure 33.

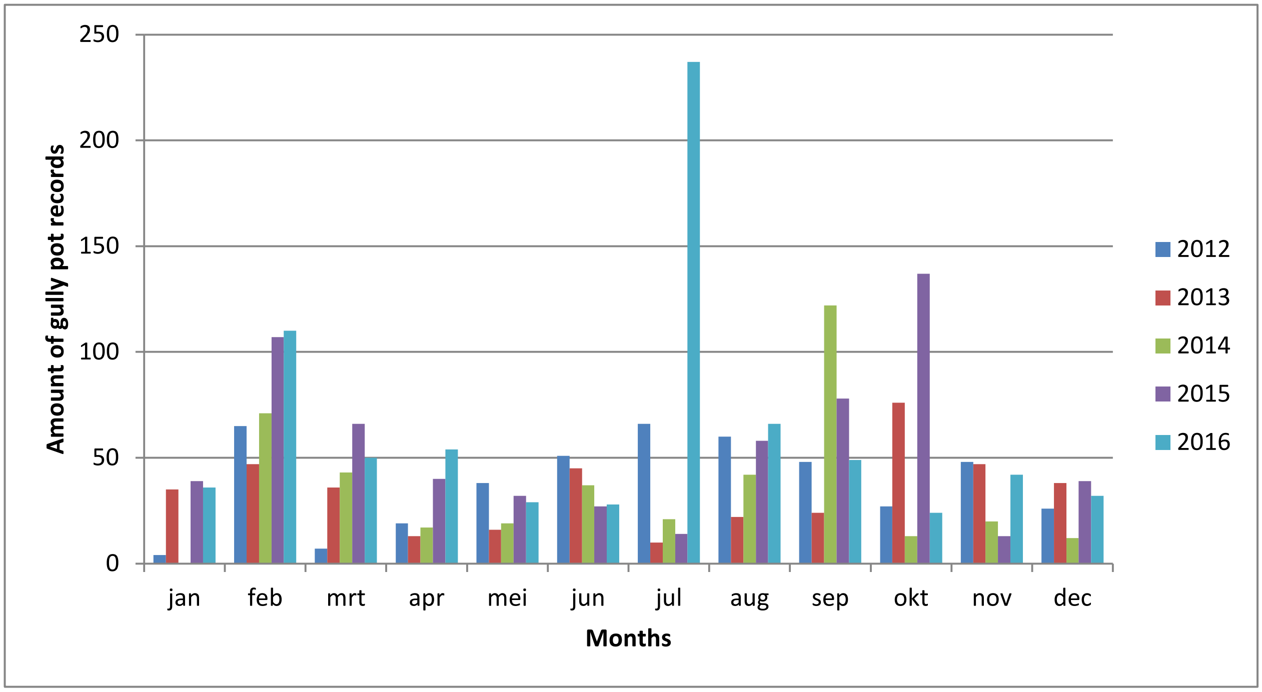

Figure 33: Gully pot records grouped by the month (2012-2016)

Next, a timeline is created from January 2012 to December 2016 with time steps of a month. For each month in this time interval, the total amount of gully pot records for all hot spots are shown. To be able to determine whether flooding records are caused by natural or human factors (system overloading by rainfall versus gully pot blockage by leaves), it is important to include an analysis of the accumulated rainfall over the months within this time interval. This can be observed in Figure 34. Rainfall data from rain stations Rotterdam Airport, Hoek van Holland, Pernis and Rozenburg is used.

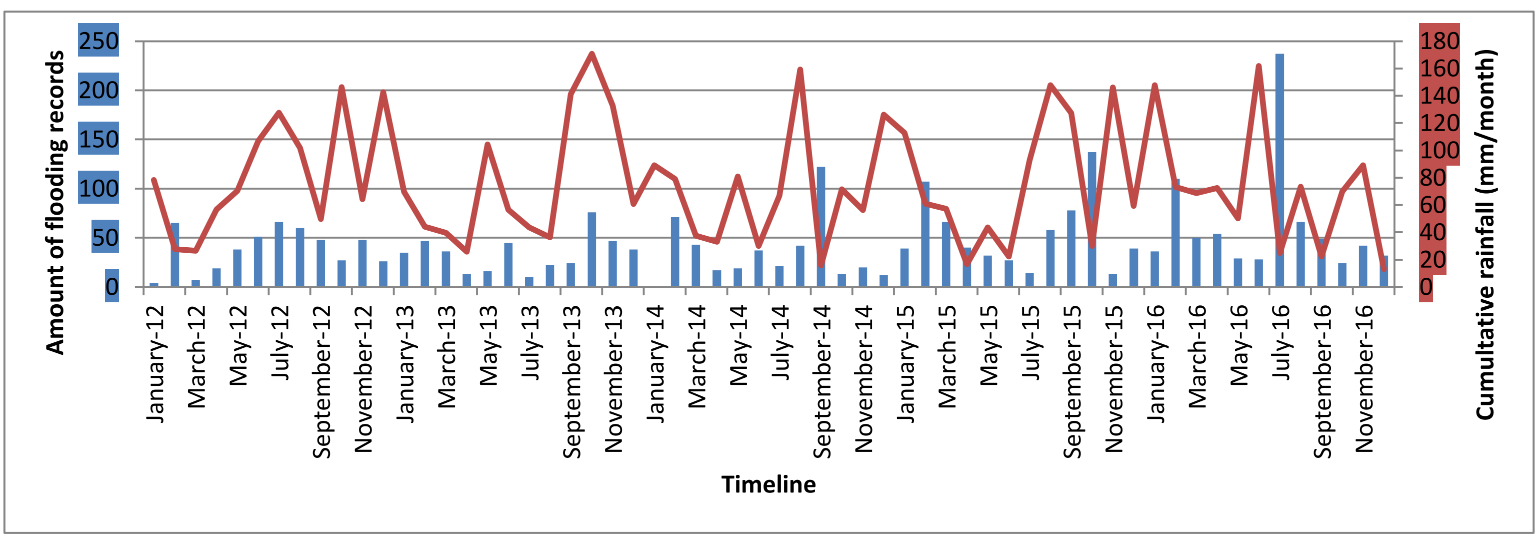

Figure 34: Timeline of the amount of flooding records and cumulative rainfall (averaged over all hot spots, Jan-12/Dec-16)

The theory to make the distinction between natural or human factors is as follows. If the amount of cumulative rainfall is very high, then the probability is higher that system overloading occurs. If the amount of cumulative rainfall is quite low, but the amount of flooding records is very high, then the probability is higher that the flooding incidents are caused by blockage of gully pots by leaves. This is taken into account while checking Figure 34 for seasonal patterns. It would obviously be more ideal to have a longer timeline to check for seasonal patterns, but five years should be sufficient to check for repeating patterns. It appears that there are two type of repeating patterns, in one winter time and one in summer time. They can be observed at the points where the blue bars intersect with the red line in Figure 34. These points are located in the timeline as follows:

- Summer: July/September ’14, September/August ’15, June/July ‘16
- Winter: Jan/Feb ’12, Jan/Feb ’15, Jan/Feb ’16.

For both the Summer and Winter pattern, the same phenomenon occurs. In the first mentioned month, a peak in cumulative rainfall can be observed, which is followed by a large decrease in cumulative rainfall and a large increase in flooding records in the second month. A plausible theory behind this is as follows. A month with a very high amount of rainfall can cause leaves (or garbage) to be transported. If such a month is followed up by a month of low rainfall, but loads of flooding complaints, then that can indicate that leaves (or garbage) have ended up in gully pots, causing flooding incidents at low amounts of rainfall. For the pattern in the summer period, most of the leaves are still on the trees, but heavy rainfall can definitely cause leave fall, making it possible to block gully pots afterwards. For the winter period, leaves have dropped from the trees a long time ago, which means there has been sufficient time for the leaves to end up in the gully pots or to be transported there via the surface due to the heavy rainfall. These gully pot blockages could have been prevented if the performance of maintenance was better. Therefore, these returning patterns can be assigned to human factors instead of natural. If the timeline had been longer, there would have been more certainty in the appointment of a seasonal pattern, as in two of the five years this pattern is missing for both Summer & Winter. Additional research over a longer timespan offers ways to a stronger story instead of a plausible theory.

A shape file in the database of the Municipality has been accessed that contains point data of every tree in the Municipality of Rotterdam. This file is used to check for the presence of trees at the hot spot locations to make a connection to gully pot flooding records. However, the presence of trees is also affected by the area size. Therefore, the effect of area size on flooding records and trees has to be taken into account as well. Another correlation matrix is created, which can be observed in Table 14.

	No. of trees	Area	No. of gully pot records
No. of trees	1	0,988	0,976
Area	0,988	1	0,990
No. of gully pot records	0,976	0,990	1

Table 14: Correlation matrix of trees, area and gully pot records

From Table 14 it follows that there is an almost perfect correlation between all three factors. This can also be observed in Figure 35, where these correlation are plotted.

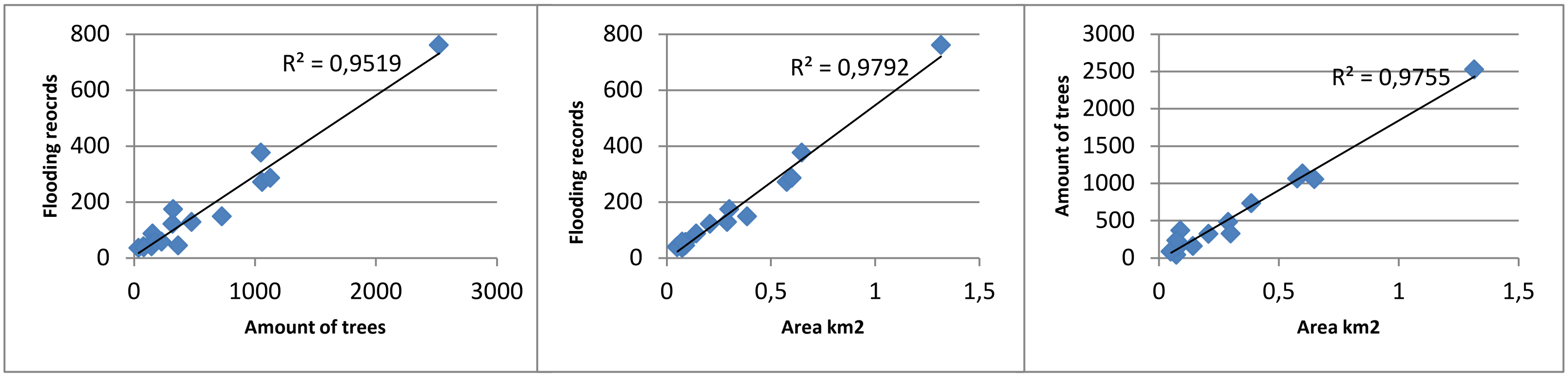

Figure 35: Relation between presence of trees, flooding records and area

Figure 35 shows that there is a linear relation between both flooding records & area size and amount of trees & area size (middle and right figure). This means that the linear relation between flooding records and amount of trees (left figure) might as well be caused by area size. If this is the only reason for the linear relation between flooding records and amount of trees, then it cannot be concluded that the presence of trees increases the amount of gully pot related flooding records. The other option is that the presence of trees does lead to increased amounts of flooding records and therefore contributes to the found linear relationship. Therefore, based on these results, a precise distinction between the influence of trees or areas size on amount of flooding records cannot be made. Amount of flooding records could well be increased be the presence of trees, but area size also plays a role in it.

Summary

In this chapter, the influence of seasonality on flooding incidents has been investigated. One of the other aims was to distinguish between whether flooding incidents are caused by human or natural factors. Based on the five years of flooding record data, there do appear to be seasonal patterns, one in Winter time and one in Summer time. This pattern for both periods is defined by a high peak of accumulated rainfall in the first month, followed by a low rainfall peak, but a high amount of flooding records in the second month. As described, this pattern can be linked to blockages of gully pots by leave fall, which means the flooding incidents can be assigned to human factors, as better maintenance could have prevented it. An increased amount of trees seems to lead to more flooding records, but this is also influenced by area size.

5. Risk & asset management analysis of vulnerable locations in the city

Water nuisance in the Municipality of Rotterdam is rare, which is good, but its prevention should not be taken for granted. Climate change is causing increased pressure on the urban drainage system and adaptation is inevitable to maintain the quality of its functioning. Asset management offers a method to analyse risk to the functioning of the urban drainage system and reduce it as much as possible. In this way, policies around the urban drainage system should be improved. The company-value matrix of the City Management department of the Municipality is used as a guideline about which calamities or impacts are acceptable (Strategienotitie, 2013). Examples of assets of the urban drainage system in Rotterdam are sewer pipes, pumping stations and pressure pipes. Asset management can also be expressed as striving for the maximum value of each asset. These values are summarized in the company-value matrix and are defined as: availability, safety, environment, living space quality, reputation, law & regulations and economy. Availability is defined by quality and functioning of the urban drainage system assets and important connecting roads. Safety relates to the prevention of incidents that do damage to civilians or employees. The value of environment addresses prevention of negative consequences for the environment and improvement of sustainability. Living space quality is about maintaining the quality of the public space, which is related to prevention of water nuisance on the streets. Reputation relates to publicity and politics. Law & regulations is defined by performing activities within a legal framework. Finally, economy is used to express finance, employment, tourism & business. The matrix shows how the different values relate to each other. The most optimal situation is reached when risk for each company value is as low as possible (Notitie Bedrijfswaardenmatrix, 2013).

One of the approaches of the Municipality to perform a proper asset & risk management analysis is by building a hydrodynamic model in 3Di. Stress tests can then be used to identify bottlenecks in the city. Some layers are still to be added to this model, to improve its accuracy. A layer that contains vulnerable flooding locations based on Municipal call center data is one of those layers. Municipal call center data has been analysed in this report and a map of vulnerable flooding locations has been created accordingly (Figure 3). These vulnerable flooding locations can be compared with asset locations to create an overview of vulnerable places or bottlenecks in the Municipality of Rotterdam. Map layers of infrastructure & traffic and elevation can contribute to this as well. With an infrastructure & traffic map, a link can be made with the company-value matrix to investigate what types of risk levels are present in the city under certain conditions. An elevation map can be used to identify height differences and (local) depressions in the Municipality. Zones with much height differences or zones with lower elevations are in theory more vulnerable to flooding incidents, as surface flow directions are affected by slope and accumulation of water on the streets is reinforced in highly impervious environments.

To create an infrastructure & traffic map, a shapefile is used that has been obtained from the Infrastructure & Traffic department of the Municipality. It shows all types of roads and the loads that they carry. These loads are defined by the average amounts of motorized vehicles passing the road segment in both directions. All of these loads are added to find the average amount of vehicles passing a specific road segment in a day. In this way, the busiest or most important roads can be identified. This infrastructure & traffic map can be seen in Figure 36.

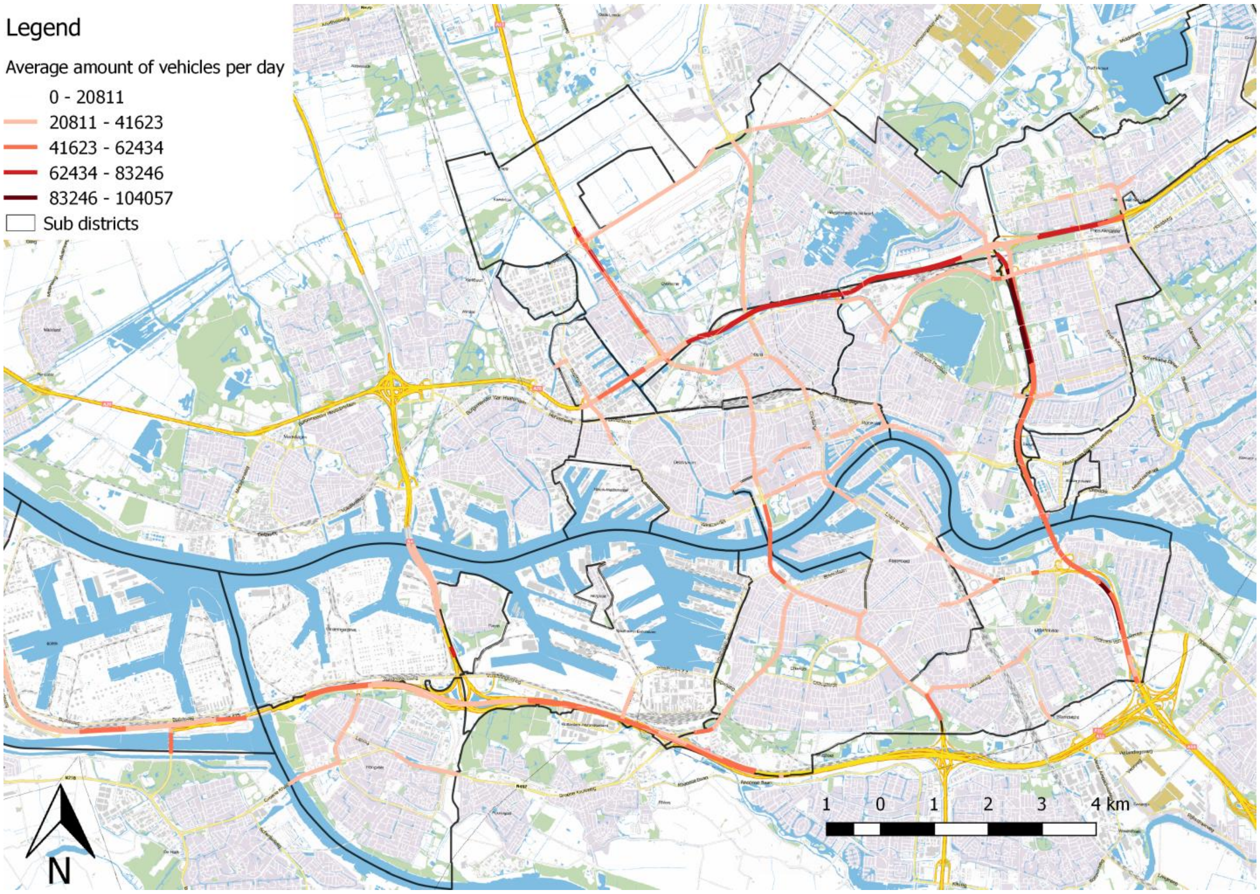

Figure 36: Infrastructure and traffic map of Municipality Rotterdam

Obviously, the highways (A4, A13, A15, A16, A20) carry the heaviest loads per day (±60.000 to ±100.000 users per day). The functioning of these highways is therefore of great importance. However, this is not the responsibility of Municipality Rotterdam. Therefore, the highways are not taken up in further analysis. In the city of Rotterdam, tunnels and bridges (Maastunnel & Erasmusbrug) are really important infrastructure links that carry the second heaviest loads (±30.000 to ±50.000 users per day). In third place, the main connecting roads throughout the city center district (±15.000 to ±25.000 users per day).

For the creation of an elevation map, raster data is needed that provides information about the surface level heights. Twenty one of these elevation raster data tiles are found in the database of the Municipality. After merging and editing them, one elevation map is created for the whole Municipality of Rotterdam. The full elevation map can be found in Figure 37, Appendix B. Since the most dominant flood prone locations are found in and around the city center, a closer look will be taken at this region by creating a zoomed in elevation map. Also contour lines are created to show any (local) depressions or gentle slopes. This can be observed in Figure 38.

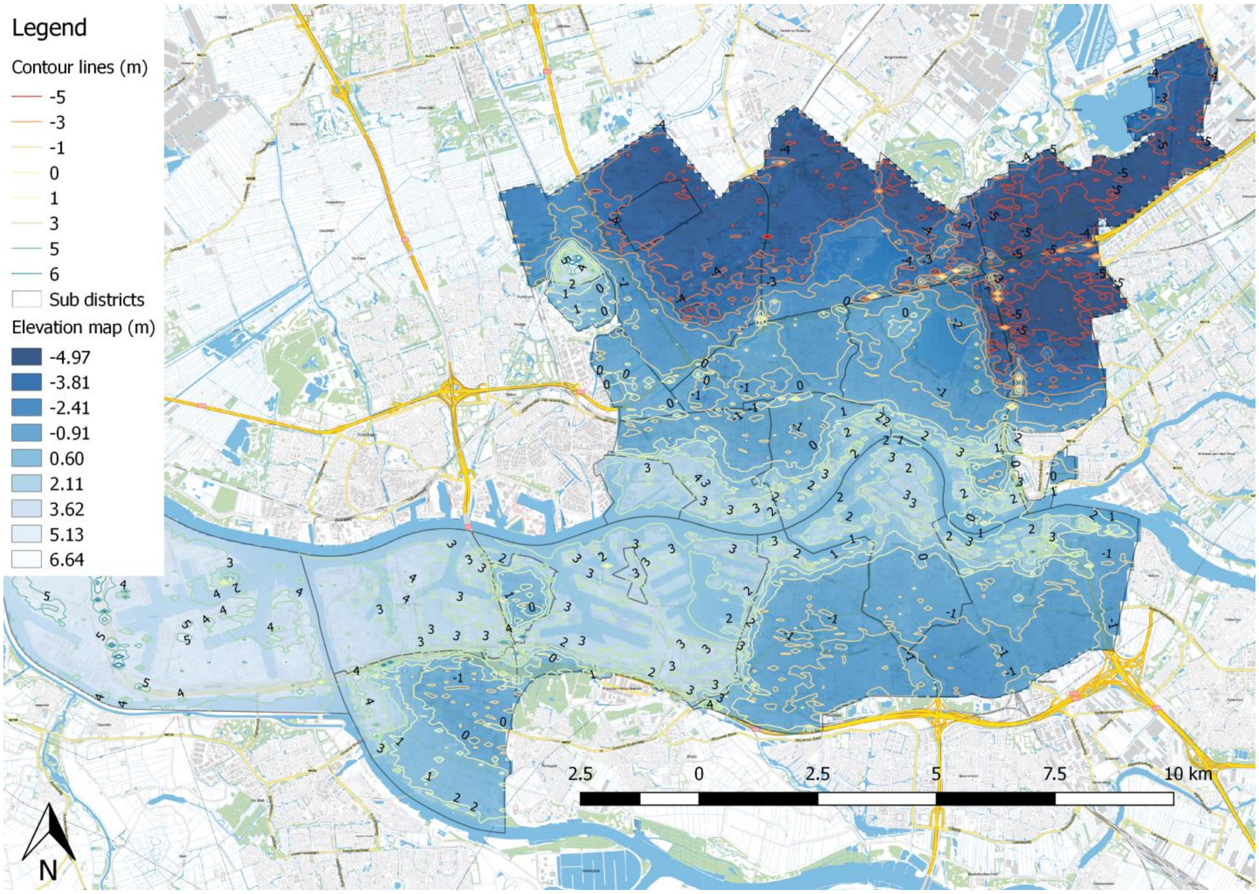

Figure 38: Elevation & contour line map of Rotterdam

A couple of elements stand out in this elevation map. First of all, there is a large area in the north east of the Municipality of Rotterdam that has a quite low elevation. To be more precise, this low lying area covers parts of the Prins Alexander, Hillegersberg Schiebroek and Overschie sub district. As mentioned earlier, low lying areas can be more flood prone, as water accumulates more easily here. However, this is not really relevant in a pumping station regulated urban water system. Therefore, rainfall that falls on this area does not necessarily imply a higher flooding probability or a more flood prone area. The second element that stands out, which might have more significance, is the height difference between the heart of the city center (Noord, Centrum, Delfshaven) and the height of the urban area to the south, adjacent to the Nieuwe Maas river. It can be observed that the city center area is situated around -1m (below NAP) to 0m, while the area to the south of it has an elevation of 1-3m above NAP. This might cause redirecting of surface runoff towards the city center district, making that area more flood prone, which might be one of the reasons that the biggest identified flooding hot spots (Figure 3) are actually situated in the city center district. To further investigate this, height profile lines are drawn across the city center area. This can be seen in Figure 39.

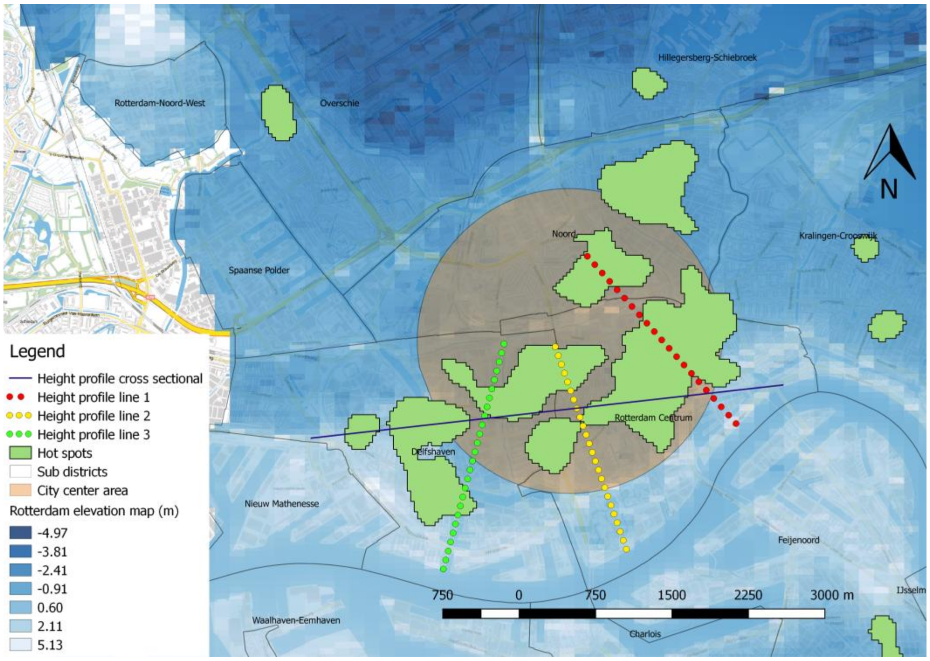

Figure 39: Height profile lines in the city center area of Rotterdam

Elevation levels are retrieved from the elevation map and used to plot the surface level height differences along the height profile lines. These profiles can be observed in Figure 40 & 41 below.

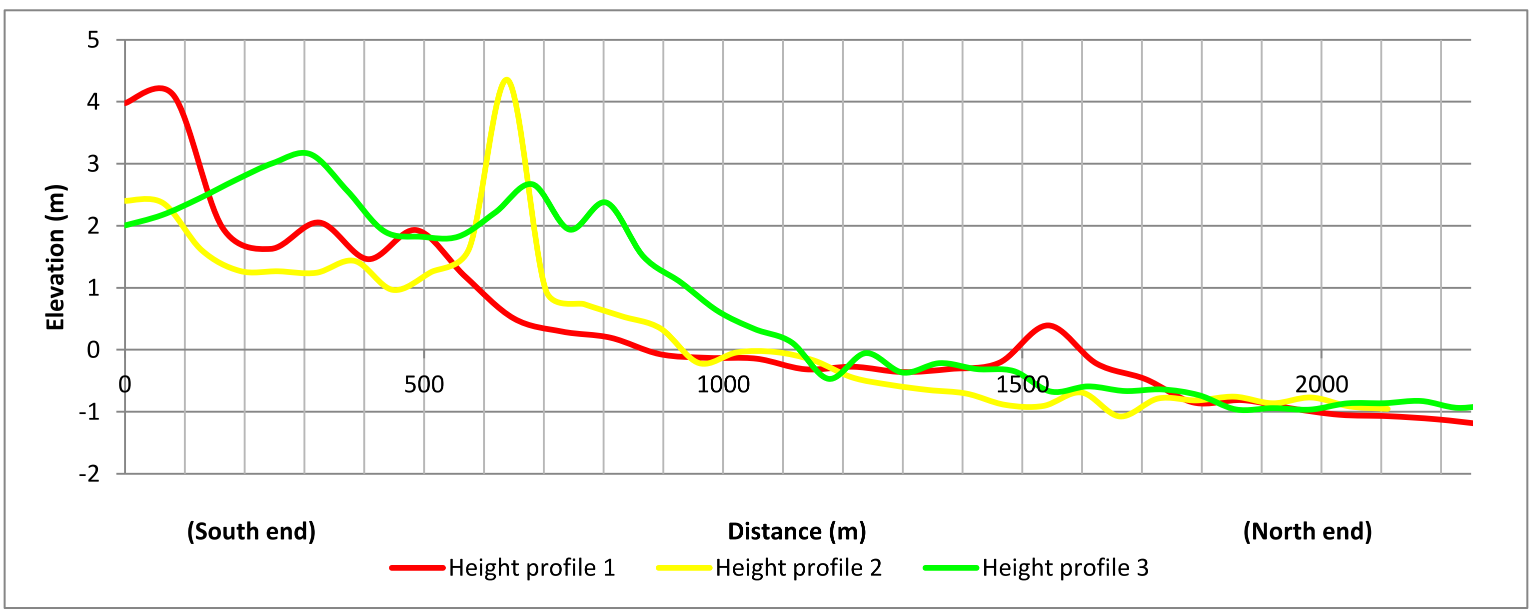

Figure 40: Height profile lines 1,2 & 3

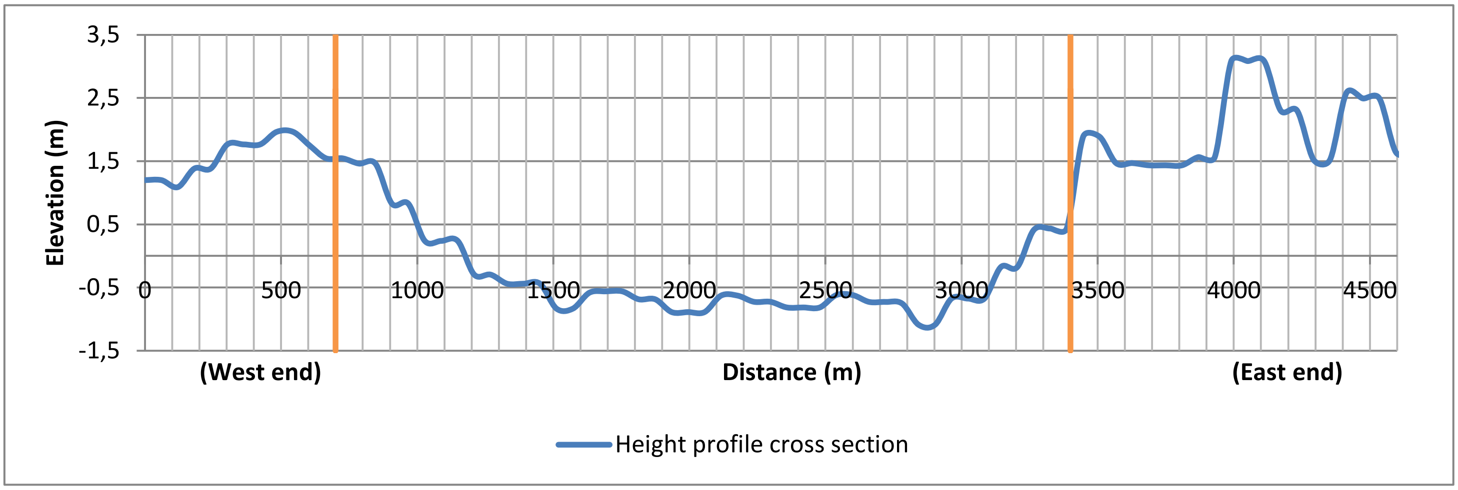

Figure 41: Cross sectional height profile level (orange vertical lines represent city area circle boundaries)

The height profiles of Figure 40 & 41 confirm the theory that was derived from elements of the Rotterdam elevation map (Figure 38). The city center area indeed has a lower elevation than the surrounding area to the south. From Figure 40 it follows that surface runoff towards the city center should be possible. In the first ±700m distance of height profile line 1, 2 & 3, there are some small peaks that correspond with embankments or heightened roads. After this, a relatively unimpeded downward gradient towards the city center can be observed, allowing surface runoff to flow to the lowest point. The large city center hot spots are situated in this downward sloping or low lying area. In Figure 41, a cross sectional height profile is constructed to also investigate the elevation behavior in a West-East direction. It can again be observed that downward slopes towards the city center are found and that the city center has a lower elevation than the surrounding areas. The two vertical orange bars correspond with the intersection points of the cross sectional height profile line and the circle in Figure 39 that roughly indicates the city center area. The area contained between the two orange bars has two downward slopes on both sides and a low lying area in the middle. Therefore, by combining Figure 39, 40 & 41, it follows that there is a downward slope from the West, South and East (of the city center) towards the city center. This could increase flooding problems in the city center area, which is something that appears to be true, based on the identified flooding hot spots that are situated there.

The analysis above focuses on Rotterdam's surface level and redirecting of surface runoff due to surface level elevation differences. This does not take into account civil structures in the city like tunnels and underpasses, which are often situated about 3 to 4 meters below surface level. They can therefore be seen as very local slopes and depressions, which also cause redirecting of surface runoff and hence accumulation of water at the bottom. In a lot of cases, one or more pumping stations are present at the bottom of those civil structures to pump excesses of water out in times of heavy rainfall. However, it is still possible that water accumulates and causes infrastructure & traffic blockages, if the water level becomes too high. This can for example be caused by pumping station failures, blockages of inlet structures or overloads of water that exceed pumping capacities. Therefore, as they form additional bottlenecks, these civil structures are relevant to take into account in the risk & asset management analysis. Most of these civil structures can be found around the city center area, similar to where the most dominant flooding hot spots are found. An overview of this is given in Figure 42 below. The black dots and lines represent the present tunnels and underpasses. It can be seen that quite a few of these are actually situated within the identified flooding hot spots.

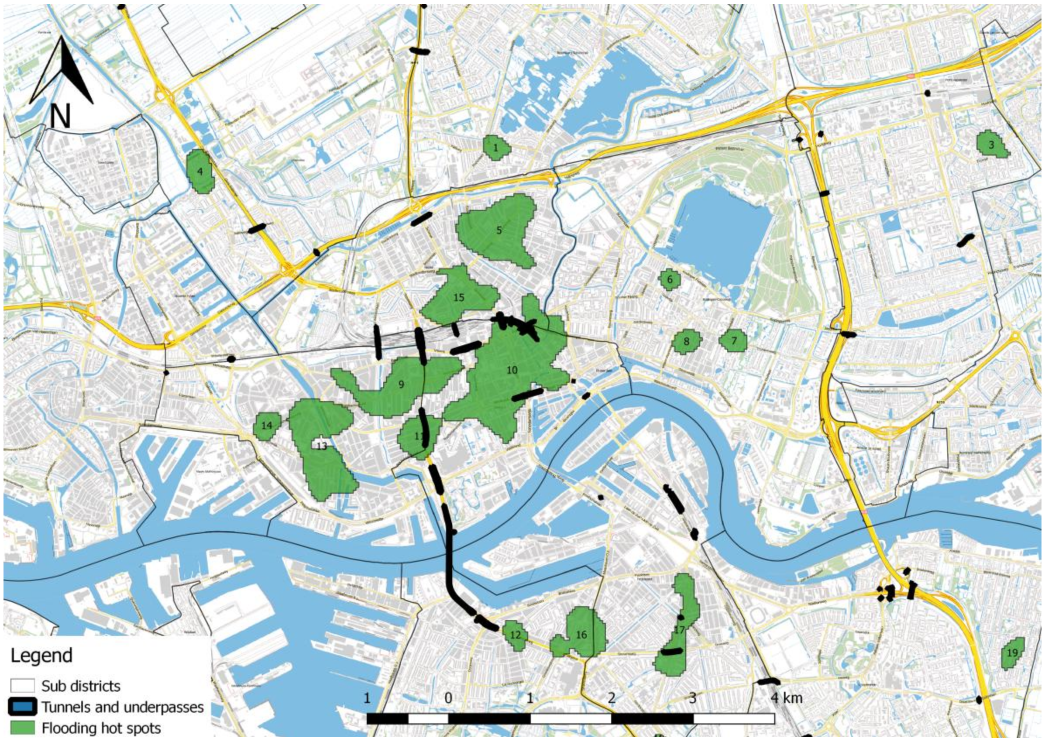

Figure 42: Tunnels, underpasses and flooding hot spots in Rotterdam

An investigation of the Rotterdam elevation map pointed out that redirecting of surface runoff towards the city center might contribute to the flooding problems there. The biggest flooding hot spots are found in the city center area and slope can be one of the problem factors. The city center area is therefore extra important to further focus on in the creation of the risk map. To be able to link vulnerable areas and important assets to different degrees of risk, a link has to be made with the company values as well as occurrence frequency of water nuisance. The company-value matrix can be found in Figure 43, Appendix C. Risk is found through this matrix by multiplying an impact to a company value with the right occurrence frequency. Risk is expressed by Safe (S), Low (L), Medium (M), High (H), Very High (VH) and Extreme (E). Based on the results and data used in this report, risk can be expressed for two company values, which are: availability & living space quality. These two values are relevant, as compromised chains in the urban water system network or compromised (connecting) roads can be related to (heavy) rainfall. The impact of network chains or roads that are compromised is expressed in user days. A user day is defined as the amount of users during the duration (with the unit of days) that an asset is compromised. This relation can be seen in Formula 3.

$$User\ days = Average\ amount\ of\ users\ per\ day * duration\ of\ unavailability \quad (3)$$

For example, if a road is flooded for 2 hours and the average amount of vehicles per day is 10000, then the impact expressed in user days equals: $User\ days = 10000 * \left(\frac{2}{24}\right) = 833.3$. Using this definition allows for making the connection between flood prone areas and infrastructure (defined by average amount of users per day). To characterize present risks in the city, occurrence frequency is needed. This occurrence frequency is related to heavy rainfall and return times of different intensity events. In the Netherlands, cloudbursts or extreme rainfall, like events 16 to 19 (±30mm/40min or ±50mm/24 hours) in this report, have an occurrence frequency which is characterized as 'Incidental' (0,03-0,3 times/year). According to Module C2150 (2009), the following relations can be defined between rainfall intensity and degree of nuisance (Figure 44).

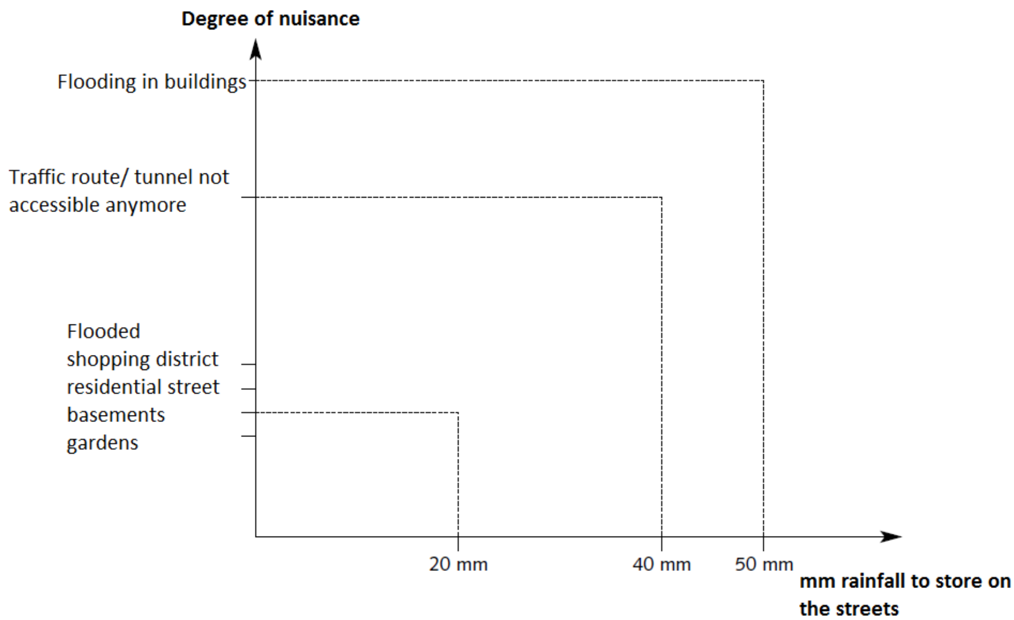

Figure 44: Relation between rainfall intensity and degree of nuisance

On the x-axis in Figure 44, rainfall depth can be seen that has to be stored on the streets. On the y-axis, negative impacts or different degrees of nuisance to different assets can be observed. Logically, higher rainfall intensities require more storage on the streets. Hence, the higher the water level of stored water on the streets, the higher the potential damage. What also follows from Figure 44 is that a rainfall event of 20mm/hour corresponds with a possibility of water on the streets or in gardens. Rainfall events of 40 to 50mm can have more severe consequences, like flooding of traffic routes or tunnels and flooding in buildings. A 20mm water layer on streets or in tunnels is quite likely with such an event. Since this event can have a significant impact and a not unlikely occurrence probability, it is chosen as a threshold to analyze what type of risk it creates. As mentioned, the occurrence frequency of an event of 40-50mm of rainfall is 'Incidental' (0,03-0,3/year). Furthermore, for this type of event, the connection can be made with the company values 'Living Space Quality' and 'Availability', as there is a very high probability of water nuisance on the streets or flooding of buildings or tunnels. This follows from historical data of complaint records during these type of rainfall conditions. In comparing the company values of 'Living Space Quality' and 'Availability', it appears that there is a factor of 2000 between them. For example, if an event has an extreme impact, then this corresponds with >2500 user days for the value 'Living Space

Quality' and >5.000.000 for the value 'Availability'. Apparently, 'Living Space Quality' has a much heavier weight on risk levels. Reasons for this can be found in the fact that network chain disturbances ('Availability') do not usually cause life threatening situations, while water on the streets ('Living Space Quality') is more related to people's safety. For example, a layer of water on the streets can cause manhole covers to become heavy floating obstacles, while they leaves open holes behind. This is a recipe for very dangerous situations.

To calculate the actual risk that can be produced for the values of 'Living Space Quality' and 'Availability', occurrence frequency has to be combined with the corresponding amount of user days for a road segment, a tunnel or a main traffic route. For the company value of 'Living Space Quality', risk will be expressed for the whole infrastructure network, to get an idea of what the overall risk level is for the whole city, according to the present company value matrix (Figure 43, Appendix C). For the company value of 'Living Space Quality', risk will be calculated for the most important tunnels, which are not only good indicators for main traffic routes, but they are also flood prone due to the slope and low elevation. The locations of these tunnels or main traffic routes can be seen in Figure 42. To find the right amount of user days for the two company values above, a couple of assumptions are made. Firstly, for the 'Living Space Quality' value, it is assumed that a 40-50mm rainfall event causes water nuisance on the streets for a duration of an hour. Secondly, for the 'Availability' value, it is assumed that a similar event can cause network chain disturbances (flooding of tunnels) for a duration of two hours. This means that 'duration of unavailability' is now known (Formula 3). 'Average amount of users per day' (Formula 3) is also known through the infrastructure & traffic map (Figure 36). The amount of user days that the assets are affected can now be calculated. Also, all information is known to calculate corresponding risk levels with the company value matrix. Two risk maps are produced for the company values 'Living Space Quality' and 'Availability'. They can be seen in Figure 45 & 46. The colors of the risk levels in these map correspond with the risk level colors in the company value matrix.

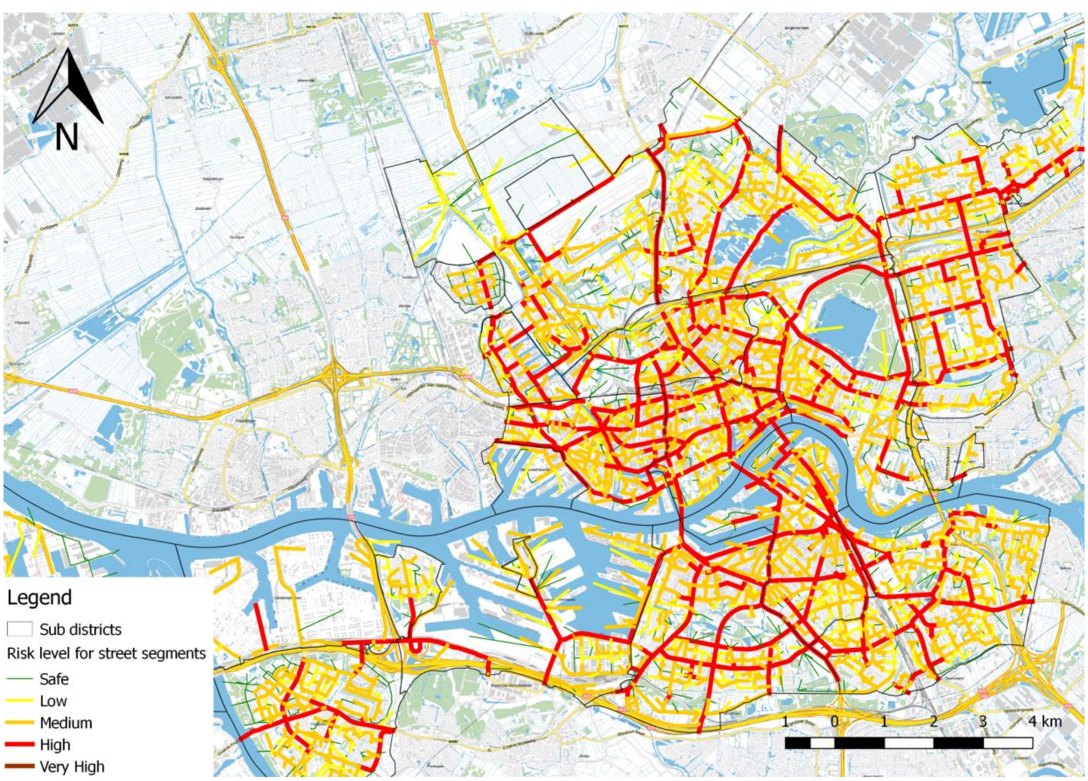

Figure 45: Risk map based on company value 'Living Space Quality' (water nuisance on the streets)

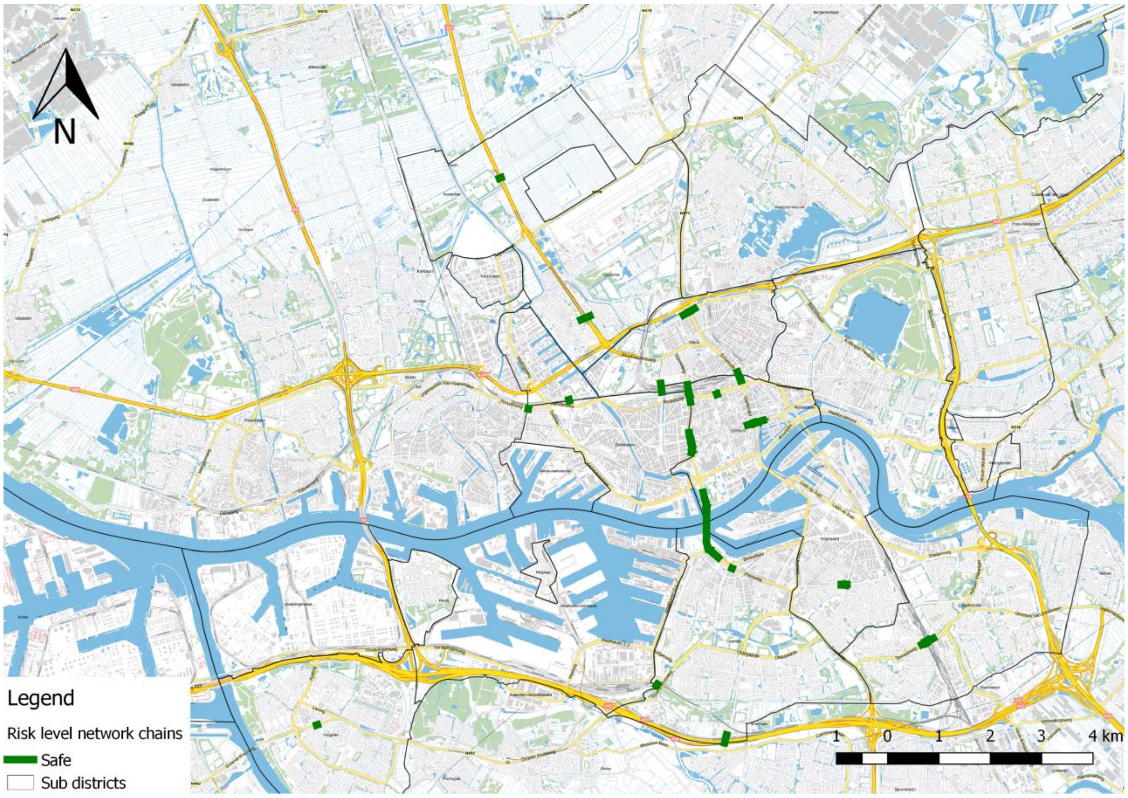

Figure 46: Risk map based on company value 'Availability' (network chain disturbance)

It can be observed in Figure 45 that almost all connecting roads have a high risk level under current assumptions and properties of the company value matrix. Most of the roads however, are under medium risk. In Figure 46 it can be seen for the (main) network chains in the city (tunnels and underpasses) that there is no risk at all under current assumptions and properties of the company value matrix. Therefore, there is a big contrast between the two company values. This contrast is mainly caused by the weight factor (of 2000) between the values. Based on these results, it is highly questionable whether this factor is appropriate. A two hour disturbance of the busiest network chain in Rotterdam, the Maastunnel, causes no risk at all under current settings of the company value matrix. This is probably not the desired or expected outcome.

Since the city center districts appears to be most vulnerable to flooding incidents, it might be illustrative to zoom in a little on this area and show the produced risks for some well-known streets. The risk map of Figure 45 will be used for this, as this risk map gives the most pronounced results. The zoomed in map that is created from this can be observed in Figure 47. The main street that runs through the middle of this image in a somewhat North-South direction is the Coolsingel. Under the current assumptions (rainfall event of 40-50mm and 1 hour disturbance time), the Coolsingel is appears to be under high risk. The same applies for the street Westblaak, that intersects the Coolsingel in a West-East direction.

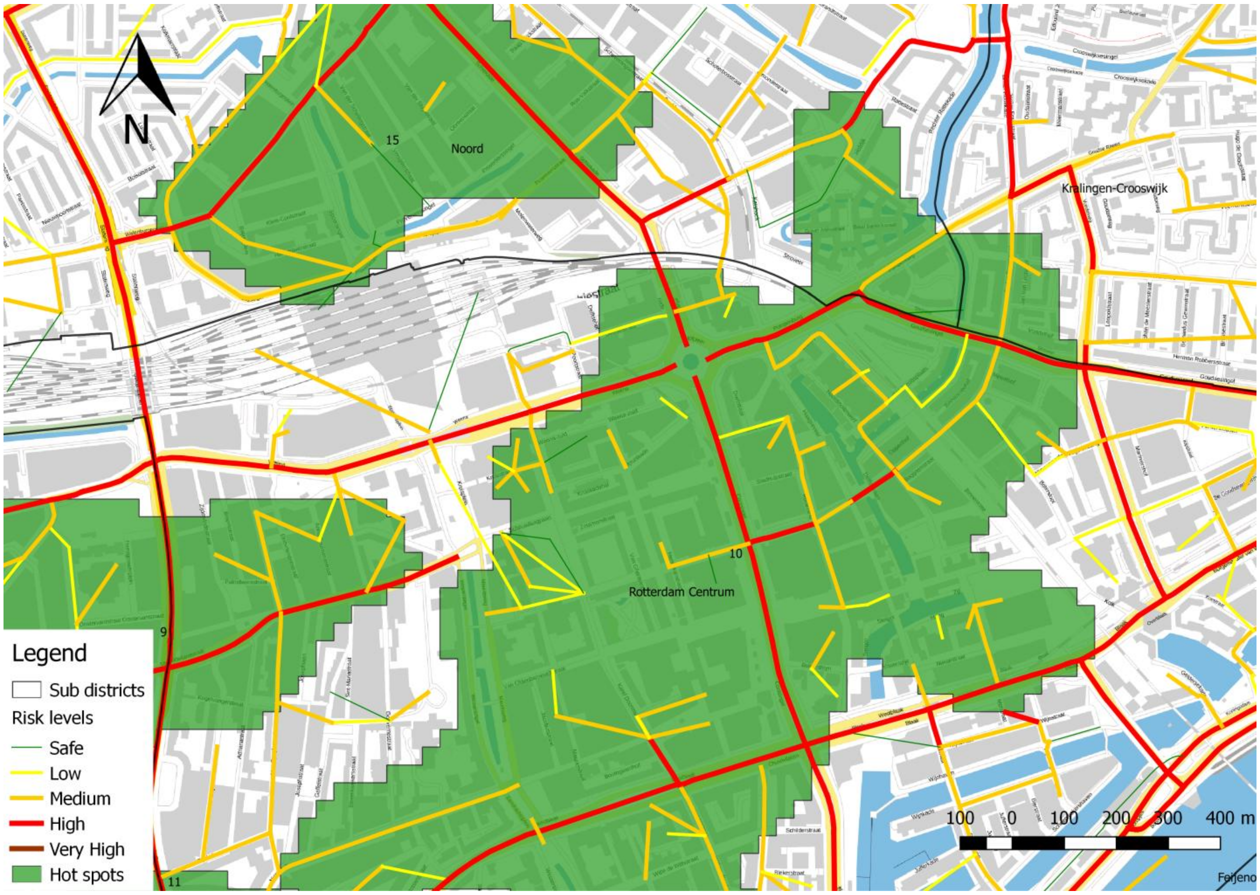

Figure 47: Zoomed in risk map for company value 'Living Space Quality'

The risk maps above (Figure 45 & 46) are qualitative risk maps. To perform a quantitative analysis of the risk levels for both company values, the disturbed lengths of roads and tunnels are calculated and summed. The exact figures can be found back in Table 15, Appendix A. To express the results of this analysis visually, Figure 48 is created. It shows for both company values a quantitative comparison of the different risk levels. It is not strange that the amount of kilometers for the company value 'Availability' is really small compared to those of 'Living Space Quality', as 'Availability' only concerns network chains and not all roads in the Municipality. However, it is questionable that 'Availability' only produces the 'Safe' risk level. As mentioned earlier, this is caused by the weighting factor that might be too high.

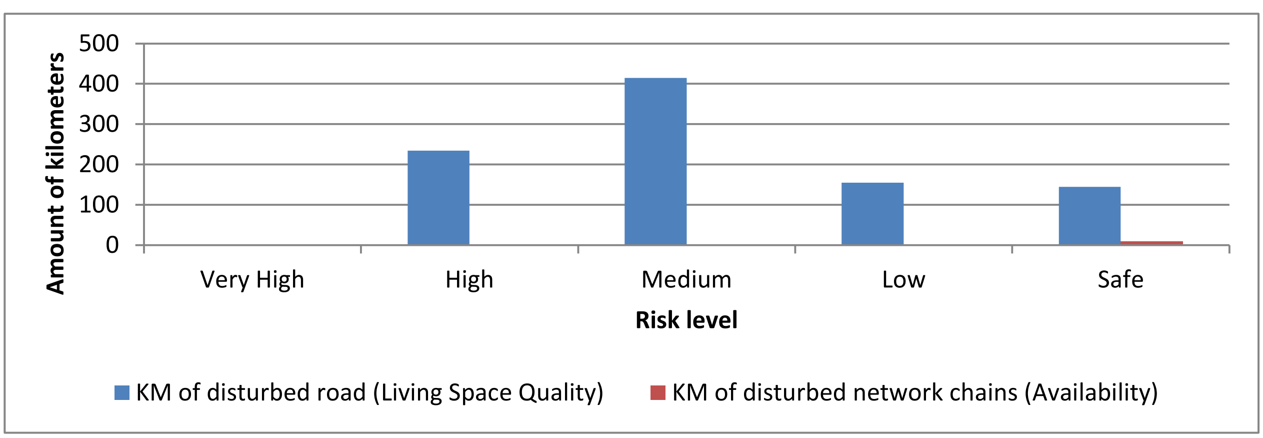

Figure 48: Bar chart of risk levels quantified in terms of affected asset lengths

Summary

An infrastructure & traffic map is created that shows the average amount of users per day on each road segment. These figures are needed to calculate to amount of user days, which is used to express how much the assets are affected. An elevation map of the Rotterdam Municipality is also created and is used to check for depressions or height differences. It follows from the elevation map and from height profiles that the city center area of Rotterdam has a lower elevation than the adjacent areas to the West, South and East. There also appears to be a relatively unimpeded slope from the higher adjacent areas towards the city center. This might contribute to the flood prone locations found there, through redirecting of surface runoff. Assets like tunnels, which represent (important) network chains, are taken up in the analysis to make the connection with the company value 'Availability'. All road segments in the Municipality are analyzed to make the connection with company value 'Living Space Quality', which is about water nuisance on the streets. Through the company value matrix, a qualitative and quantitative risk analysis is performed for the two company values mentioned above. It follows that under the made assumptions and settings of the company value matrix, the value 'Living Space Quality' is quite susceptible to risk, while 'Availability' is not. This is mainly caused by a weighing factor, in which 'Availability' is considered to have a 2000 times less impact than 'Living Space Quality'. Re-evaluation of this weighing factor might result in more realistic risk levels for the 'Availability' company value.

6. Sensitivity analysis

In this chapter, approaches and outcomes throughout the report will be analyzed to see how sensitive results are and to address uncertainty. Simplifications or assumptions, if present, will be discussed to investigate what type of effect this potentially has on the results.

In the first chapter, the assumption is made that every flooding record gives a representative image of the actual flooding problems that occur. In fact, if this assumption is not made, no valuable information can be subtracted from the record data at all. After all, citizens will not complain for no reason, which means that the complaints represent actual flooding problems of such a degree that citizens do not find it acceptable anymore. Obviously, not all flooding records will be a hundred percent accurate. The flooding records originate from complaint calls received from civilians who do not have expert knowledge about urban drainage system assets and their failure mechanisms. Neither do the call center workers that answer the complaint calls from the civilians. Therefore, there is a good chance that complaint calls are assigned to the wrong category. Therefore, to increase the accuracy of the investigation, all of the flooding records (2012-2016) are filtered for misfits or for entries lacking descriptions. Flooding records that lack descriptions are deleted from further investigation and misfits are reassigned to the right category. This is mainly performed by using text filters on the problem description column in the complaint record files. The corrected flooding record data set is used for further analysis. A heat map is created based on all of the flooding records. The actual hot spots that are found is dependent on the radius of heat map function. If the radius is chosen to be large, one big blur would be found in the city center instead of multiple hot spots. Choosing a smaller radius results in more specific hot spots, which allows for determining the most vulnerable hot spots more precisely.

In the second chapter, statistics of the flooding records are investigated. Despite the fact that the problem categories of the flooding records might not always be a hundred percent accurate, it follows from Figure 9 and 12 that gully pot records are by far the most dominant problem category. The sewer problem category is second biggest one. The other categories only represent a small part of the amount of flooding records. The subdivision of problem category contributions corresponds with the knowledge of the Municipality about the origin of urban flooding problems, validating the investigation results. In the imperviousness investigation, average runoff coefficients are selected out of a range for each land surface type. These ranges are defined by multiple scientific sources. However, in times of heavy rainfall, when urban flooding problems are at its highest, films of water reside on impervious surfaces and pervious surfaces are (partially) saturated. This means increases the amount of surface runoff and thus runoff coefficients. Therefore, runoff coefficients will now be chosen at the top of the defined ranges, to see how this affects the calculated percentages of imperviousness for the postal code zones. The new runoff coefficients can be seen in Table 16 below.

Land type category	Runoff coefficient
(Semi) paved or infrastructure	0.90
Buildings	0.95
Unpaved	0.35
Remaining	0.95

Table 16: Runoff coefficients during heavy rainfall conditions

To investigate what the effect of the increased runoff coefficients is, new imperviousness ratios will be calculated for 5 highly impervious postal code zones and 5 pervious postal code zones. If the impervious zones are affected more than the pervious ones (or the other way around), then this would change the composition of the land use map. Table 17 shows the result of this investigation.

Postal code zone	% Imperv old	% Imperv new	Difference
3011	75,5	87,0	11,5
3012	76,5	88,4	11,8
3013	76,9	87,5	10,6
3014	76,4	88,3	11,9
3015	68,9	80,8	11,9
3045	42,1	55,4	13,4
3047	37,6	51,7	14,1
3056	44,1	57,4	13,3
3151	42,4	56,1	13,7
3181	44,9	58,2	13,3

Table 17: Sensitivity analysis on degree of imperviousness

It obviously follows that increasing the runoff coefficients leads to increased imperviousness for all zones. Since the differences between the old en new ratios are quite similar, the composition of the land use map would not change. This means that there is not much uncertainty in the conclusions drawn upon the map. In other words, the highly impervious city center area would remain highly impervious in comparison to the zones around it. Also, the biggest flooding hot spots would still be located in the highest impervious zones.

In the third chapter, the influence of rainfall on urban flooding events is investigated, based on the complaint records. An exponential relation is found between increasing rainfall intensity and increasing flooding records. This is based on 40 entries of varying rainfall events over a time period of 24 hours and their corresponding amount of flooding records. Uncertainty in this analysis could be reduced by scaling up the amount of rainfall event entries. However, with R^2 being 0.67 for the exponential trend line, there is already a quite clear relation. Increasing the amount of rainfall event entries would probably increase R^2, enhancing the exponential fit and the accuracy of the exponential relation. A quick calculation of the correlation coefficient shows a figure of 0.72, which confirms the interrelation between the two variables. It has not yet been investigated what the effect of antecedent moisture is on urban flooding events. Preceding days of rain before a certain rainfall event might affect the amount of urban flooding events and complaint records, which is therefore interesting to further investigate. Based on the cumulative rainfall images of rainfall event 17 & 19, spatial rainfall intensity variation did not appear to be a dominant factor in the determination of flooding hot spot locations. However, it also followed from these images that the 1x1km resolution of the Nationale Regenradar is not accurate enough to make precise distinctions between rainfall intensity on a city center scale. Increasing the rainfall radar resolution would reduce uncertainty in these type of analyses.

In the fourth chapter, the influence of seasonality is investigated. The call center data is not reliable enough to fully trust whether flooding on the streets is caused by a heavy rainfall event (sewer overloading) or blocked gully pots. Therefore, an attempt is made to derive this from seasonality influences. A summer and winter pattern is recognized and a plausible explanation is formulated. However, both type of patterns occur in three of the five years of investigated data. Therefore, there is some uncertainty about whether these patterns are actually patterns. Further investigation over a longer time period would increase the accuracy of this investigation. Also, more extensive research about the presence of trees and leave fall could be used to confirm or reject the seasonality patterns found in this chapter. Results of the investigation on trees and amount of flooding records were inconclusive, as both variables are affected by area size.

Finally, in the fifth chapter a risk & asset management analysis is performed. A variety of maps characterizing certain properties or assets in the Municipality have been developed. The link with the company value matrix is made via the values of ‘Living Space Quality’ and ‘Availability’. It follows from the risk map for the value ‘Availability’ that the amount of user days, that define impacts and risk levels, may need to be revised. It was initially assumed that a rainfall event of 40-50mm could cause a 2 hour disturbance of network chains, which only resulted in the risk category ‘Safe’. To see how sensitive this determination is, this disturbance time will be set to 4 hours and new risk levels will be calculated accordingly. To compare the results, the new risk levels will be compared with those in Figure 48. This results in Figure 49 below.

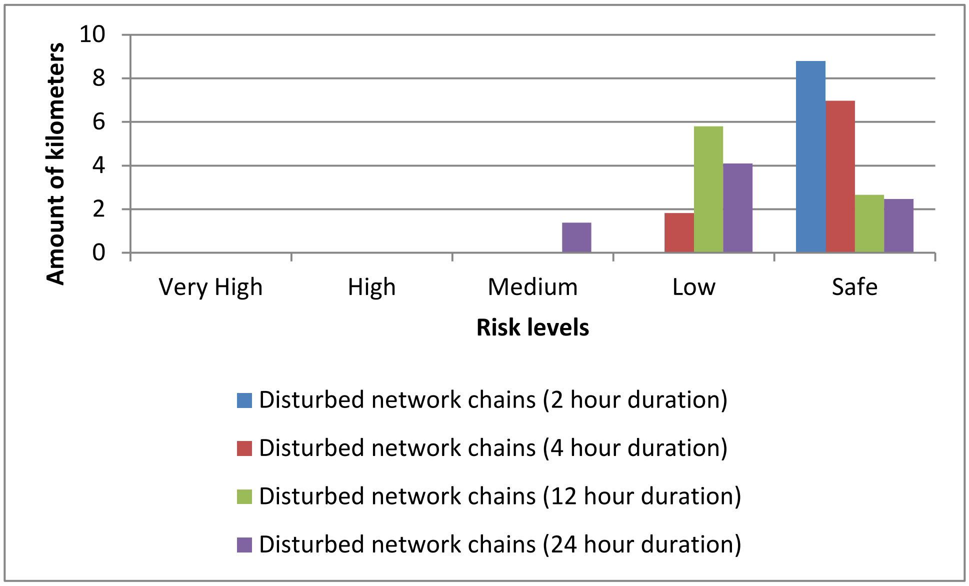

Figure 49: Risk levels for the company value 'Availability'

It follows that the previously made assumptions are not really sensitive to change, as there is not much change in the calculated risk levels. It can be seen that for a severe disturbance with a duration of 24 hours, the highest reached risk level is 'Medium' (User days: 50.000-500.000). The network chain experiencing most risk (in the "Medium" category) is the Maastunnel. These type of risk levels for network chain disturbances of multiple hours to a day is probably not the desired outcome that the company value matrix should provide.

A similar analysis will be performed for the company value 'Living Space Quality'. Previously, it had been assumed that a 40-50mm rainfall event might be able to cause flooding of streets with a duration of an hour. Risk levels have been calculated for these settings. Now, new risk levels will be calculated for disturbance durations of half an hour and an hour. The results are shown in Figure 50.

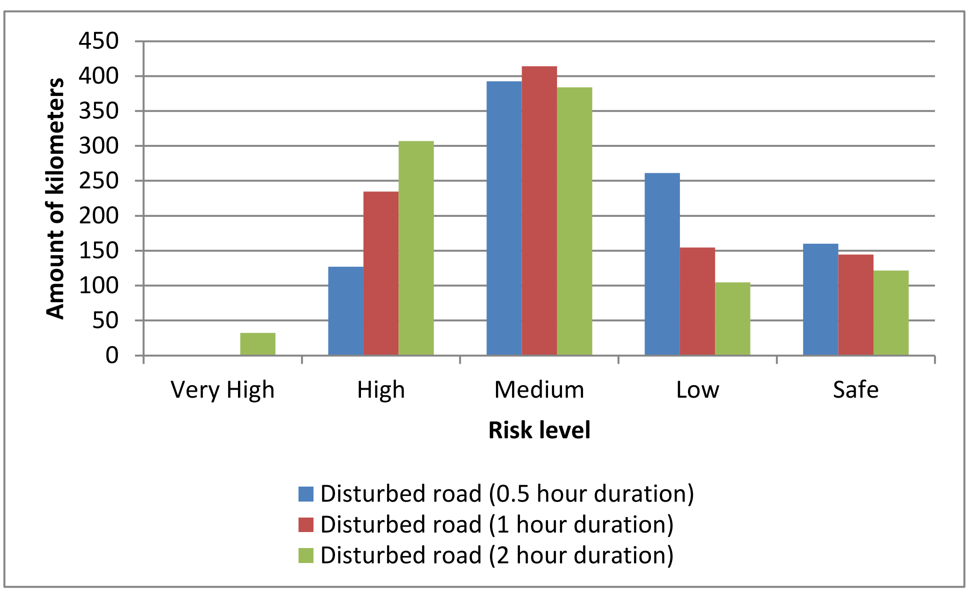

Figure 50: Risk levels for the company value 'Living Space Quality'

It follows that the company value 'Living Space Quality' is more sensitive to varying settings, as clear shifts in risk levels can be observed for varying disturbance durations. This makes sense, as more nuisance is experienced for longer disturbance durations and less nuisance for shorter disturbance durations. The reason that the risk levels for this company value are more sensitive to change can be found in the size of the impact bins. For example, it can be seen in the company value matrix (Figure 43, Appendix C) that the impact 'Proper' corresponds with 50.000-500.000 user days for 'Availability', while the bin size is 25-250 user days for 'Living Space Quality'. Since the ranges of the bins for 'Living Space Quality' are much smaller, a smaller or bigger impact is generated quicker through an adjusted disturbance time. In other words, 'Living Space Quality' has a higher sensitivity than 'Availability'. The reason for this can be found in the questionable weighing factor of 2000 that has been mentioned earlier.

7. Discussion and conclusion

In this thesis, flood-prone locations have been identified, flood vulnerability has been addressed and risk has been analyzed for the Municipality of Rotterdam. The focus to determine the flood-prone locations has been on the Municipal call center data of the years 2012-2016. It is assumed this data can be used as a representable visualization of the actual flooding incidents in the city. One could argue that the call center data is not always a hundred percent accurate, but it is based on actual flooding problems that citizens experience, otherwise they would not complain. It can therefore definitely be considered as valuable information with a social twist to it, as it gives insight in what citizens find acceptable.

In the first chapter, a heat map has been created, based on the flooding record locations, showing flood prone hot spots. A large cluster of hot spots is situated in the sub districts of 'Rotterdam Centrum', 'Delfshaven' and 'Noord'. A smaller cluster of hot spots can be found in the sub districts of 'Charlois' and 'Feijenoord'. More specific spatial analyses, like the one about the 'Flooding in Building' problem category or those about heavy rainfall events 17 & 19, result in dominant flooding hot spots in the same sub districts. From this, it can be concluded that these sub districts are indeed the most flood prone, according to citizens' experiences.

In the second chapter, the statistics of the call center data pointed out that gully pot related flooding problems are the most dominant in the Municipality of Rotterdam (≈55%), followed by sewer related problems (≈20%). The most dominant failure mechanism leading to flooding incidents appears to be gully pot blockage, followed by sewer pipe blockage. To investigate what influences flood vulnerability, the identified hot spots have been checked for the relative influence of amount of inhabitants and degree of imperviousness. It follows that there is a positive and quite linear relation between the amount of inhabitants and the amount of complaint calls. At the most dominant hot spot locations however, population density is not at its highest, validating that at these hot spots actually originate out of flood vulnerability. While the relation between imperviousness and amount of complaint calls is less pronounced, there is a clear relation between the dominant flooding incident hot spots and imperviousness. The most dominant hot spots are located within the zones of highest imperviousness, from which it can be concluded that imperviousness does have a substantial influence on the location of flooding incidents.

In the third chapter, the influence of rainfall on flooding incidents has been investigated. This is performed by plotting different rainfall event intensities versus the amount of flooding records. From this, it can be concluded that there is an exponential relation between rainfall and flooding incidents. This makes sense, as the urban water system is designed to store a certain amount of water, both in the sewer system and on the streets. Therefore, initially there will not be a lot more complaints with increasing rainfall, as long as the urban water system is still capable of draining it. However, when a point is reached that the system is fully filled up, flooding problems will arise quickly and with that, also the amount of flooding records. From comparing differences in resulting flooding records for heavy/extreme rainfall events and cloudbursts, it can be concluded that Rotterdam's drainage system is better capable at handling short heavy bursts of rainfall than very long periods of rainfall. By further investigating heavy rainfall events 17 & 19, it has been shown that more concentrated heavy rainfall events cause more problems than heavy rainfall events that are equally spread out over a long time period.

In the fourth chapter, the influence of seasonality on flooding incidents has been investigated. This is performed by analyzing the behavior of gully pot related flooding records. Since these records can originate from both sewer overloading by (heavy) rainfall and gully pot blockage by leaf fall, a monthly timeline is created of gully pot flooding records versus cumulative rainfall. There do appear to be seasonal patterns, which can be linked to blockages of gully pots by leave fall. Results of the investigation about the influence of the amount of trees on gully pot blockages were inconclusive, as both amount of trees and amount of flooding records are influenced by area size.

In the fifth chapter, a risk & asset management analysis is performed to identify potential bottlenecks in the city and to validate the company value matrix that is used to characterize risk. To make the link with the company value matrix, the average amount of users is calculated for each road segment in the Municipality. This resulted in an in infrastructure & traffic map, which is used to express how much the assets are affected based on user days. An investigation about elevation differences in the Municipality led to the conclusion that Rotterdam's city center area has a lower elevation and it is surrounded by downward slopes. This might contribute to the flood prone areas that are found in the city center, by redirecting of surface runoff. It also implies that the assets in the city center area are at more risk. Risk is calculated for the company values of 'Living Space Quality' and 'Availability'. From this, it can be concluded that 'Living Space Quality' (representing flooding of streets) is quite susceptible to risk and sensitive to disturbance time. 'Availability' (representing network chains) on the other hand is not susceptible to risk nor sensitive to disturbance time, which is probably not the desired outcome. Re-evaluation of the defined impacts for this company value might result in more realistic risk levels.

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Appendix A: Tables

Hotspot (no.)	Located in postal code zones	Located in sub districts	Area type
1	3051	Hillegersberg-Schiebroek	Residential
2	3059	Prins Alexander	Residential
3	3067	Prins Alexander	Residential
4	3043	Overschie	Residential
5	3035, 3036, 3037	Noord	Residential
6	3061	Kralingen-Crooswijk	Residential
7	3062	Kralingen-Crooswijk	Residential
8	3061	Kralingen-Crooswijk	Residential
9	3022, 3021, 3014	Delfshaven/Centrum	Residential
10	3011, 3012, 3032	Centrum	Commercial
11	3015, 3021	Delfshaven/Centrum	Residential
12	3081, 3083	Charlois	Residential
13	3025, 3026	Delfshaven	Residential
14	3026, 3027	Delfshaven	Residential
15	3033	Noord	Residential
16	3073, 3081	Charlois/Feijenoord	Residential
17	3074, 3075	Feijenoord	Residential
18	3075	Feijenoord	Residential
19	3077	IJsselmonde	Residential

Table 5: Qualitative comparison of hot spot properties

Year	Groundwater	Sewer	Lack of drainage	Malodour	Pumping station	Gully pot	Flooding in building	Total
2012	52	927	425	225	207	2459	105	4400
2013	125	782	392	262	131	1957	185	3834
2014	112	787	330	296	217	2139	154	4035
2015	193	974	394	327	244	3172	172	5476
2016	79	1146	193	295	222	3400	399	5734

Table 3: Record figures of categories

Year	Groundwater	Sewer	Lack of drainage	Malodour	Pumping station	Gully pot	Flooding in building	Total
2012	1,2	21,1	9,7	5,1	4,7	55,9	2,4	100
2013	3,3	20,4	10,2	6,8	3,4	51,0	4,8	100
2014	2,8	19,5	8,2	7,3	5,4	53,0	3,8	100
2015	3,5	17,8	7,2	6,0	4,5	57,9	3,1	100
2016	1,4	20,0	3,4	5,1	3,9	59,3	7,0	100
Average	2,4	19,7	7,7	6,1	4,4	55,4	4,2	100

Table 4: Record relative quantities of categories in percentages

Dates	Event no.	Event type	Depth (mm)	Duration (hours)
13-4-2012	1	Dry	0	N.A.
9-9-2012	2	Dry	0	N.A.
1-7-2013	3	Dry	0	N.A.
2-9-2013	4	Dry	0	N.A.
2-5-2014	5	Dry	0	N.A.
3-9-2014	6	Dry	0	N.A.
3-8-2015	7	Dry	0	N.A.
6-4-2015	8	Dry	0	N.A.
5-5-2016	9	Dry	0	N.A.
7-8-2016	10	Dry	0	N.A.
11-11-2012	11	Light	5	24
13-5-2013	12	Light	5,3	24
19-9-2013	13	Light	5,2	24
16-10-2014	14	Light	5,1	24
11-12-2014	15	Light	4,8	24
11-6-2012	16	Heavy	25	1
13-10-2013	17	Heavy	71	24
4-6-2016	18	Heavy	31	0,67
23-6-2016	19	Heavy	47	24

Table 8: Dry, light rain and heavy rain event information

Date of event	Event number	No of records	Intensity mm/24h
23-12-2012:	20	24	19,4
31-08-2012:	21	66	26,6
06-02-2013:	22	35	9,2
11-09-2013:	23	41	13,2
14-09-2013:	24	8	10,7
16-05-2013:	25	29	14,4
21-05-2013:	26	88	12,1
04-11-2013:	27	140	27,4
09-03-2013:	28	19	23,6
09-09-2013:	29	36	30,8
10-09-2013:	30	106	31,3
08-05-2014:	31	15	10,6
21-10-2014:	32	14	11,6
28-12-2014:	33	6	14,6
08-07-2014:	34	16	18,8
26-08-2014:	35	85	24,5

Table 12: Additional rainfall events

Hot spot	Gully pot records
1	35
3	44
4	86
5	271
6	40
8	50
9	285
10	760
11	121
12	40
13	375
14	56
15	148
16	128
17	173
18	37
19	57

Table 13: Gully pot related flooding records per hot spot

Risk category	KM of vulnerable road	KM of vulnerable network chains
Very High	0	0
High	234,5	0
Medium	414,2	0
Low	154,7	0
Safe	144,4	8,79

Table 15: Quantitative analysis of risk levels for company values 'Living Space Quality' and 'Availability'

Appendix B: Figures and graphs

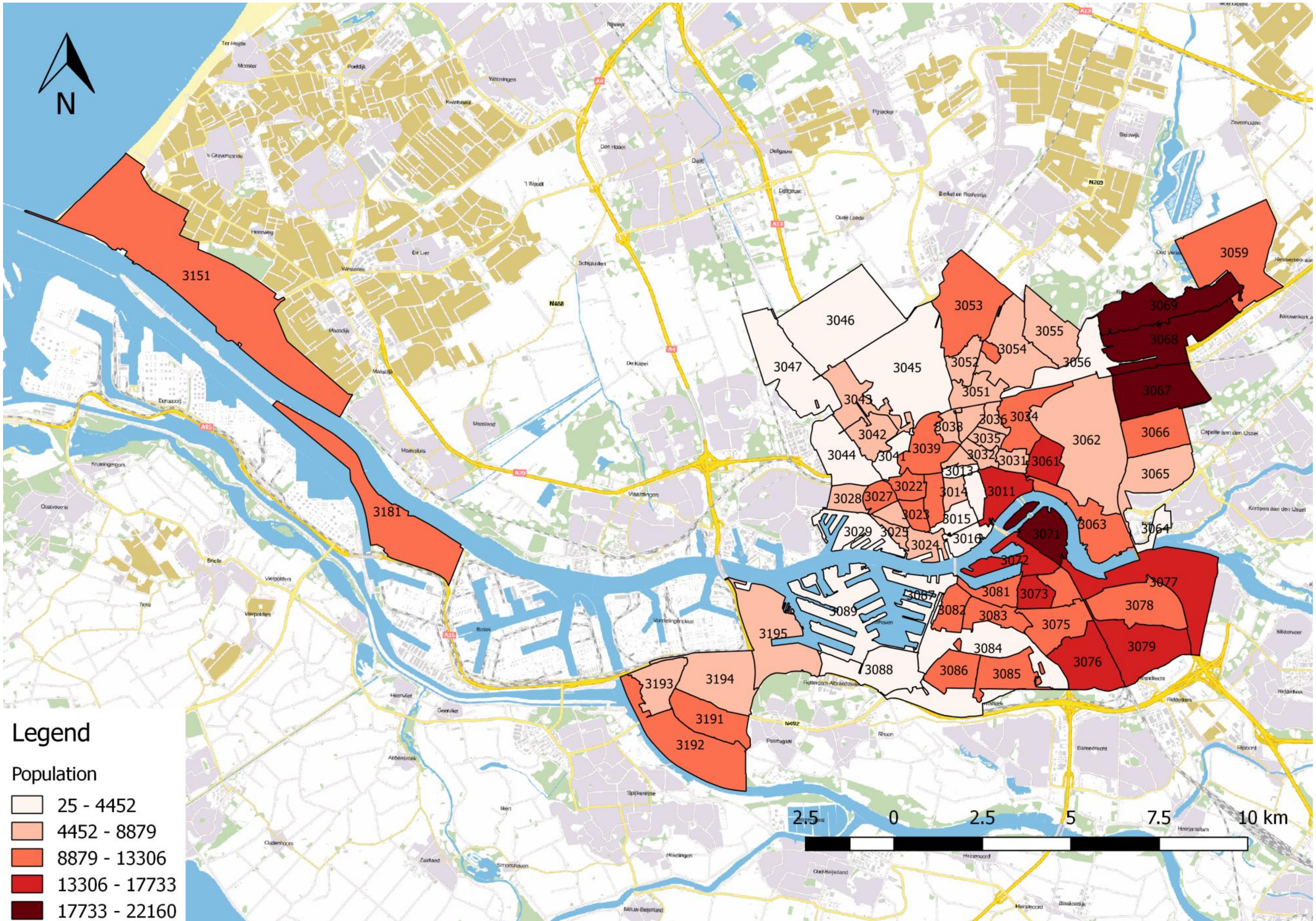

Figure 6: Population distribution per postal code zones in the Municipality of Rotterdam

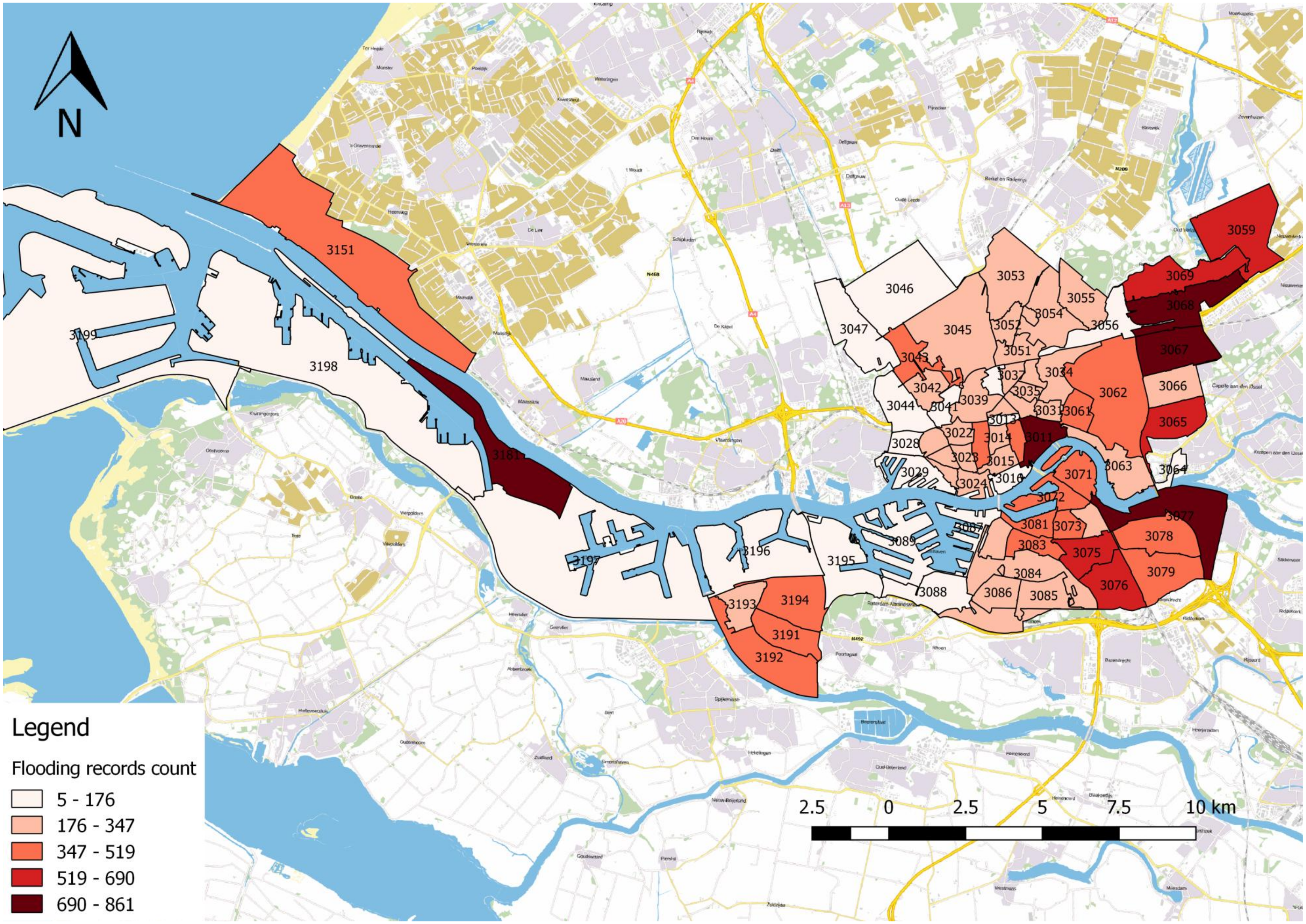

Figure 7: Distribution of flooding records based on a count per postal code zones in the Municipality of Rotterdam over the years 2012-2016

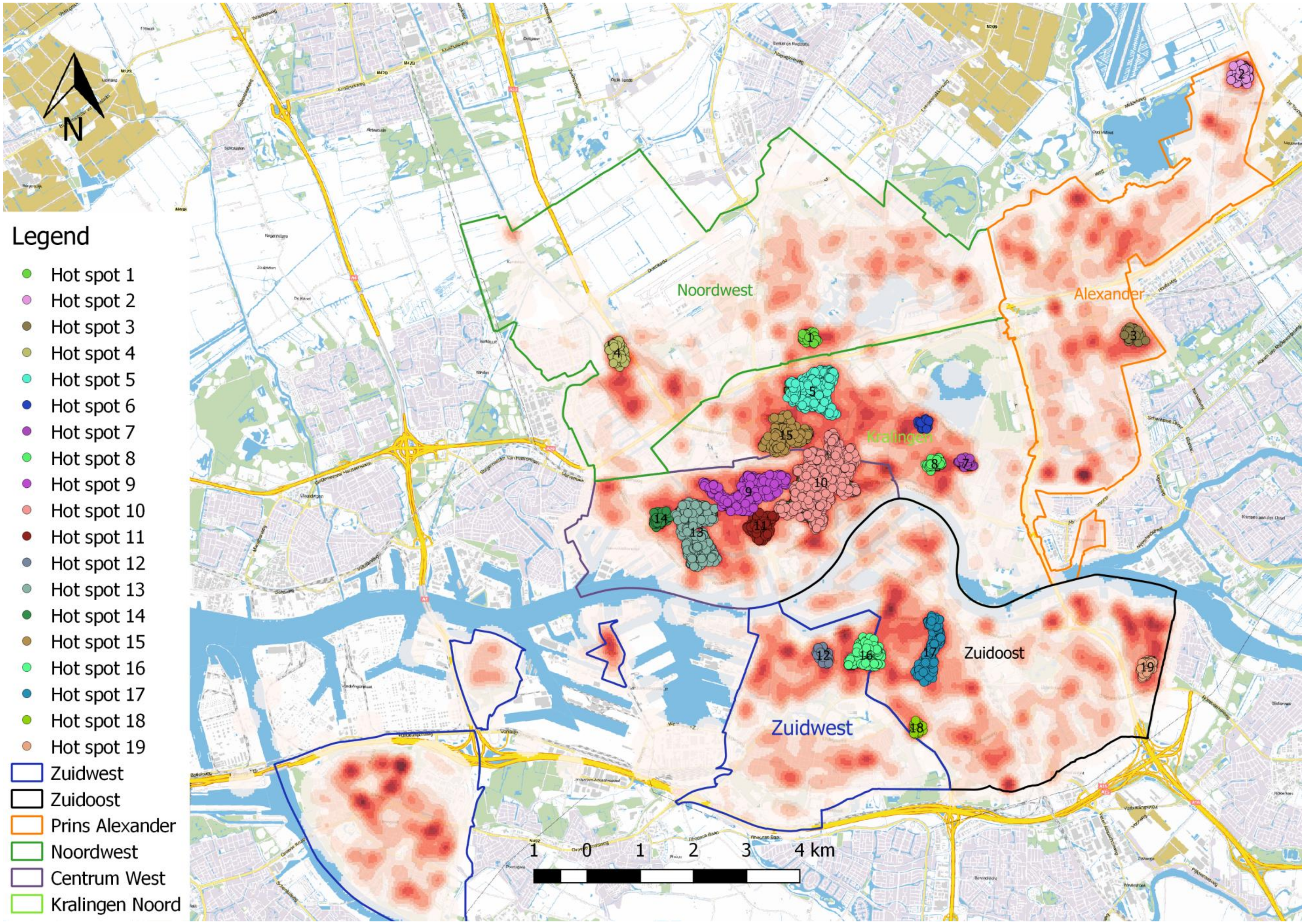

Figure 11: Flooding records sorted by hot spot areas

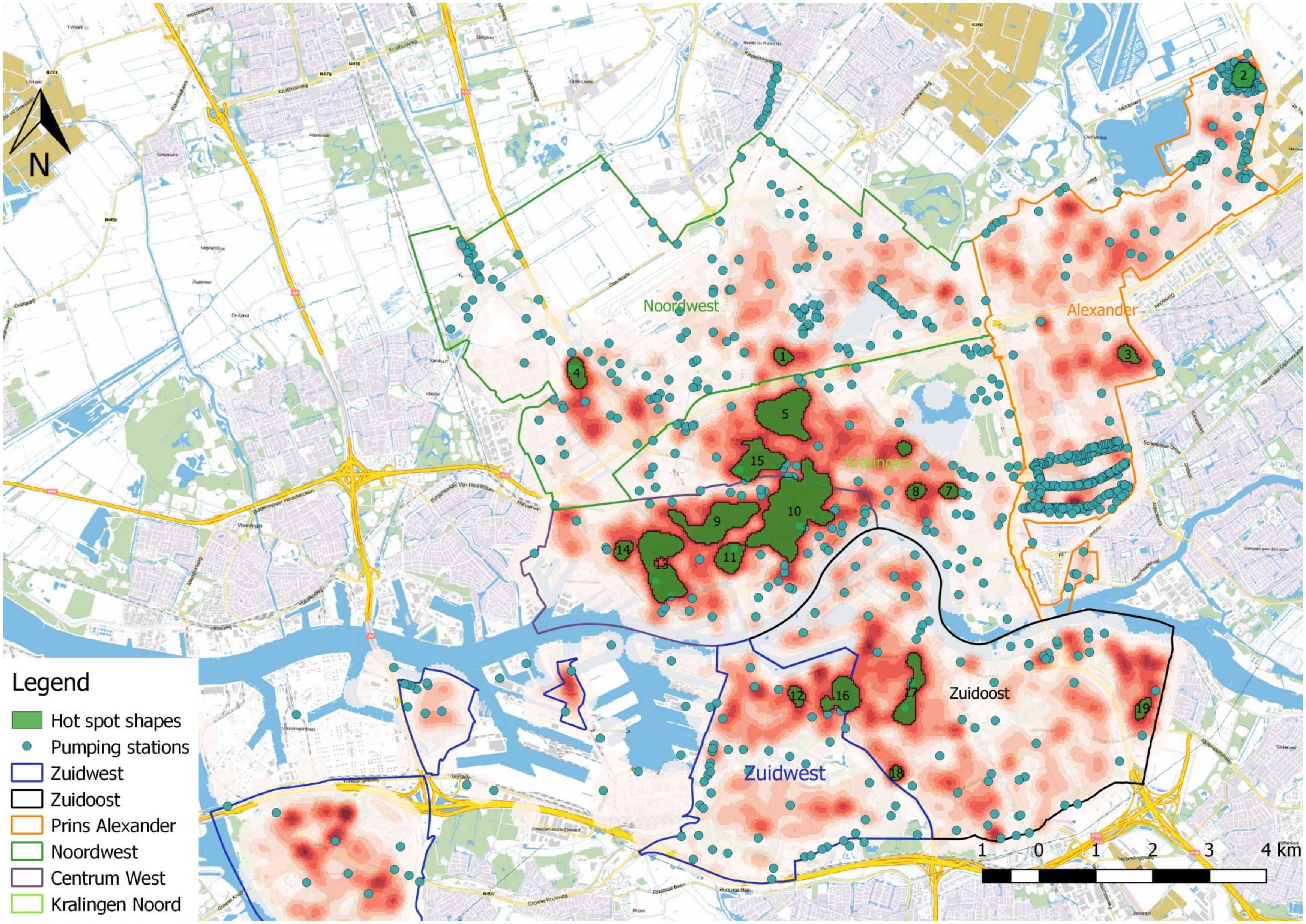

Figure 13: Pumping station distribution in the Municipality of Rotterdam

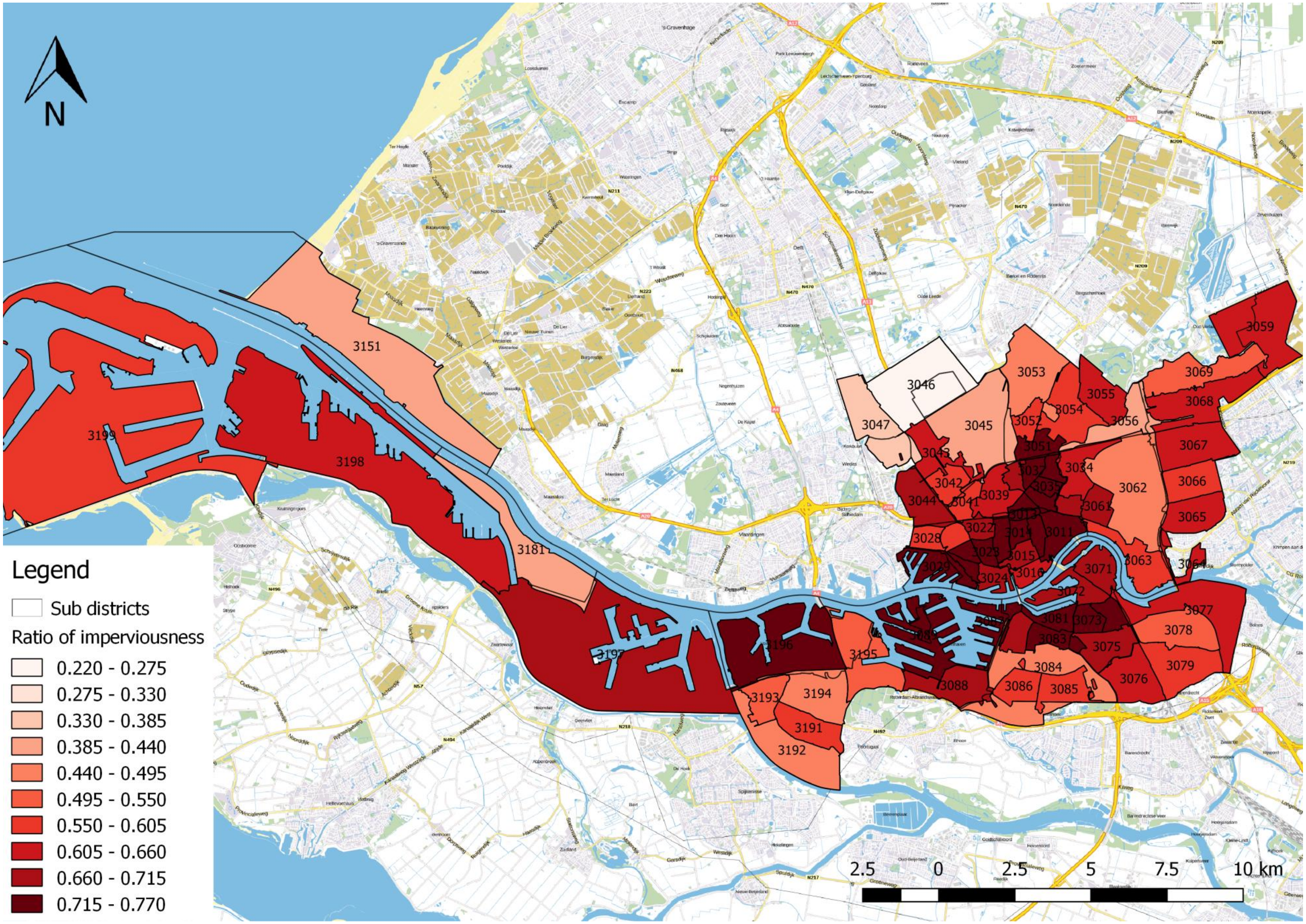

Figure 15: Degree of imperviousness per postal code zone for the whole Municipality of Rotterdam

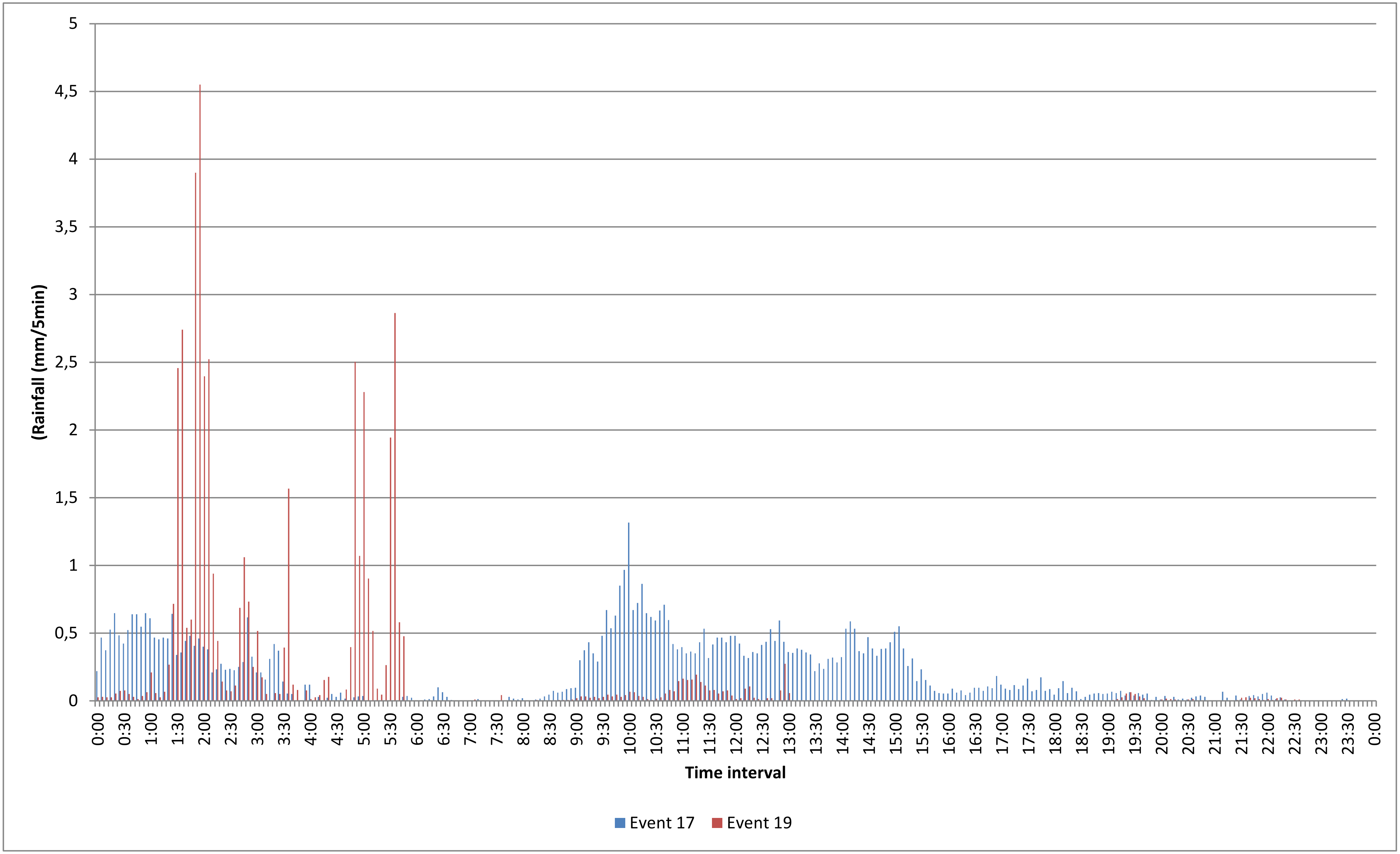

Figure 20: Rainfall intensity distributions for heavy rainfall event 17 & 19

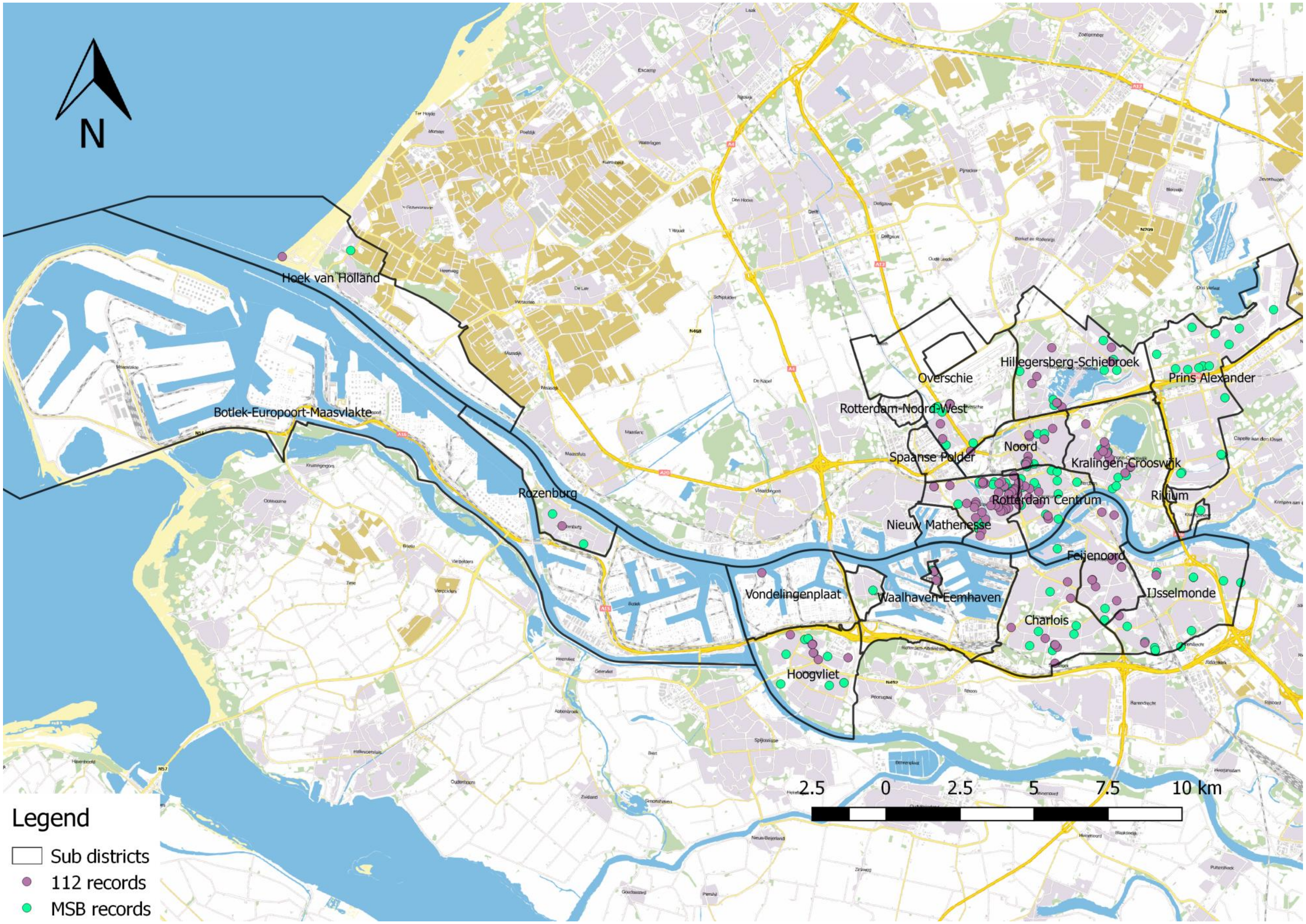

Figure 23: Flooding records for heavy rainfall event 17 (112 = emergency records, MSB = Municipality call center data)

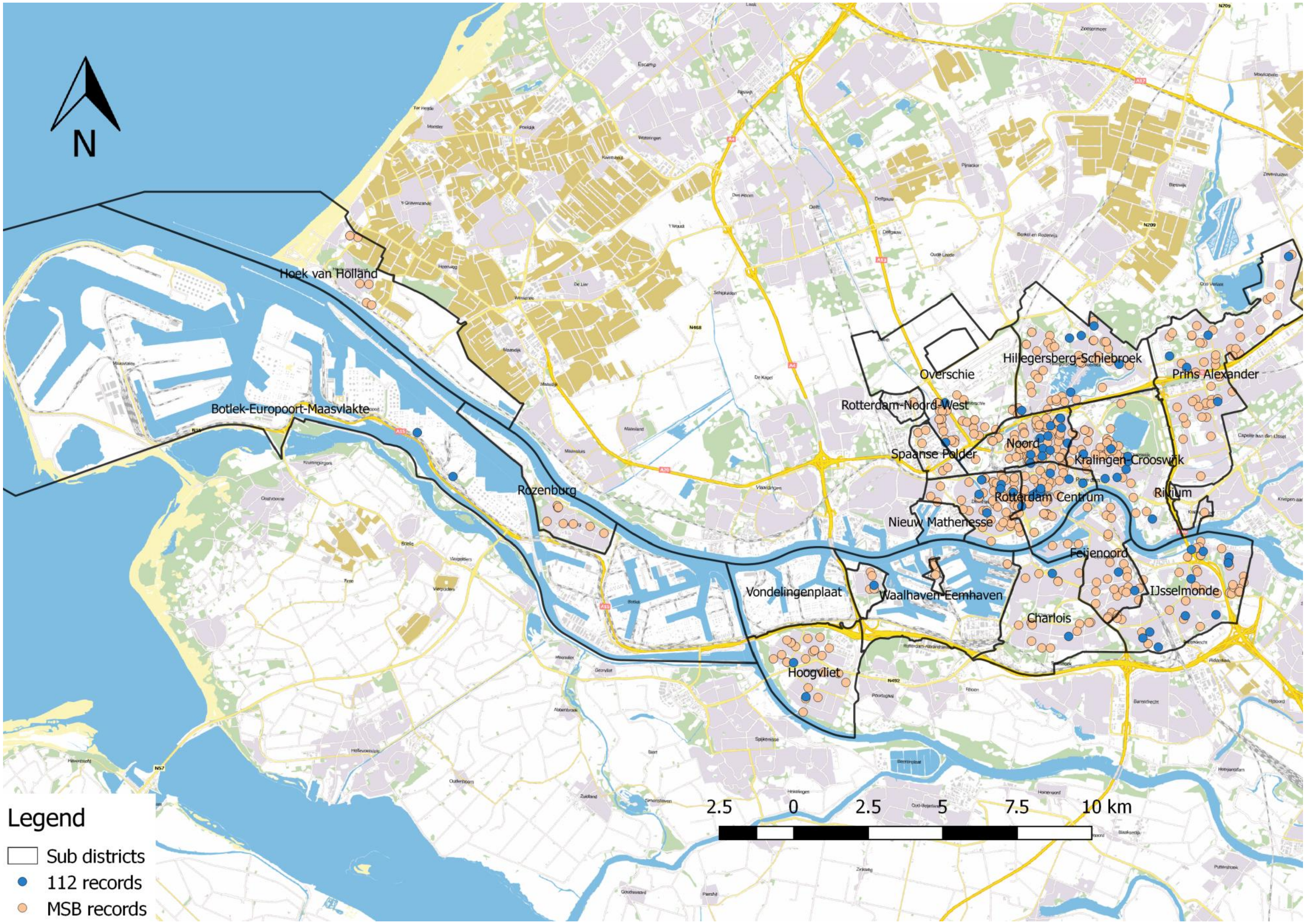

Figure 24: Flooding records for heavy rainfall event 19 (112 = emergency records, MSB = Municipality call center data)

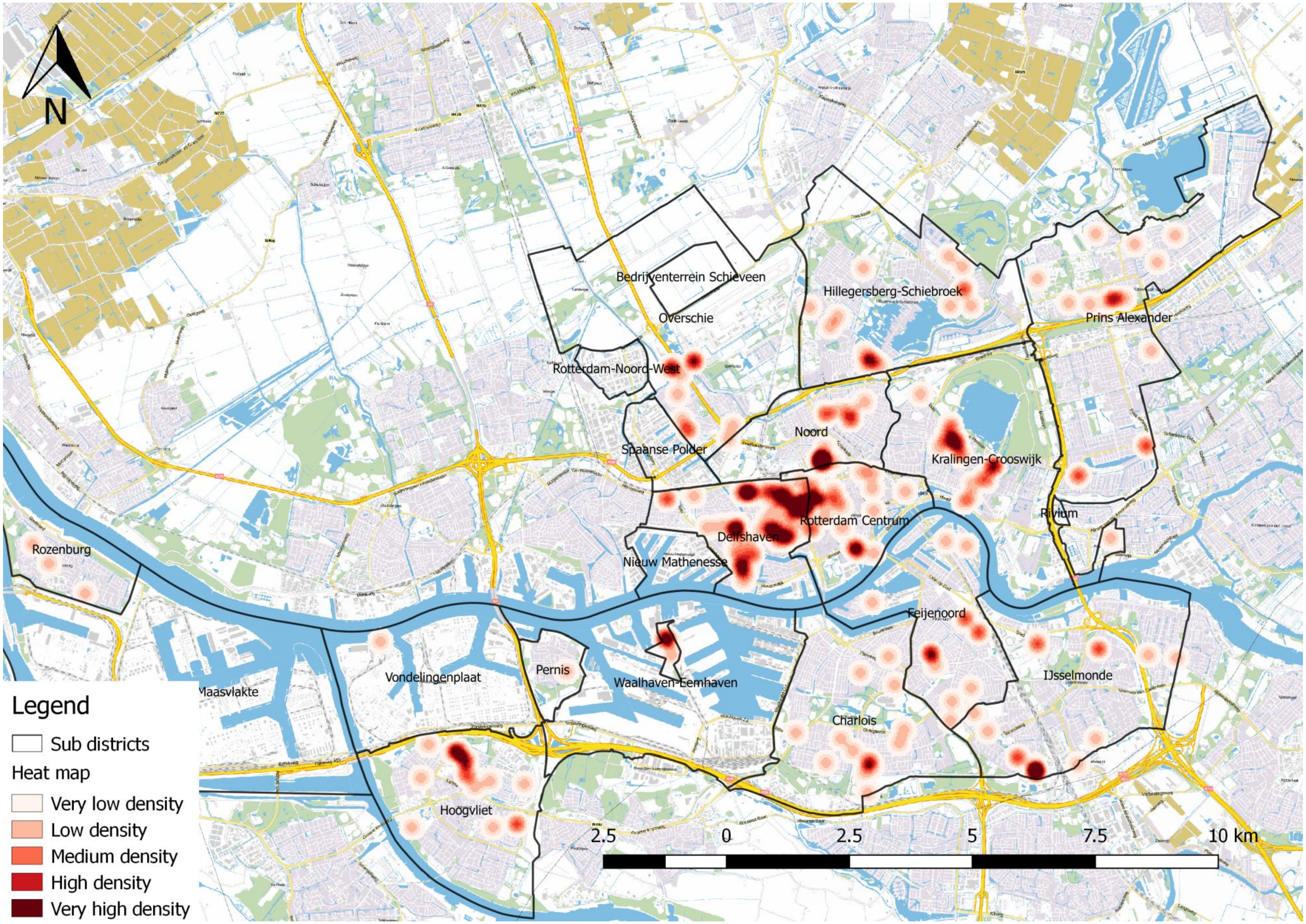

Figure 25: Heat map for heavy rainfall event 17

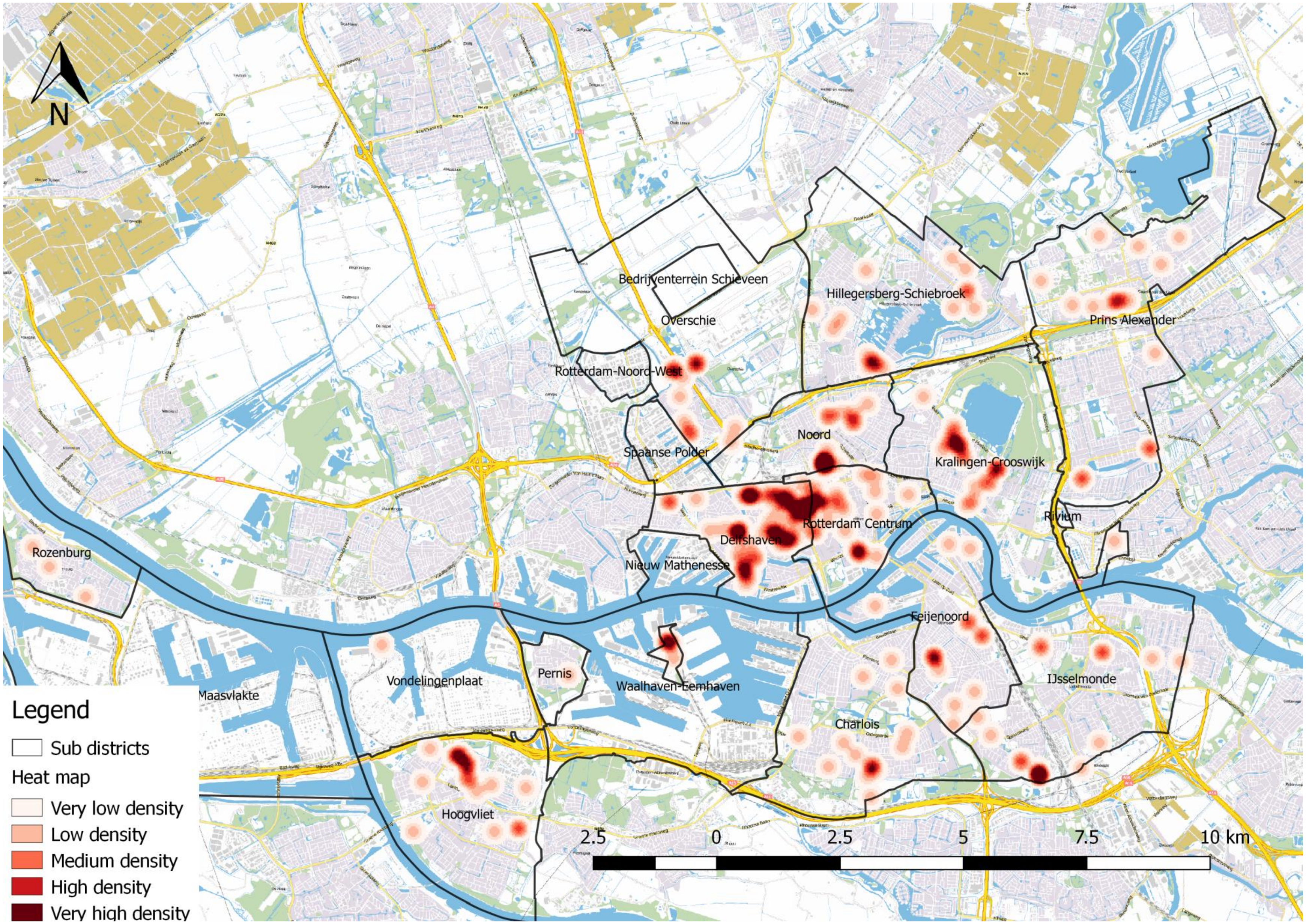

Figure 26: Heat map for heavy rainfall event 19

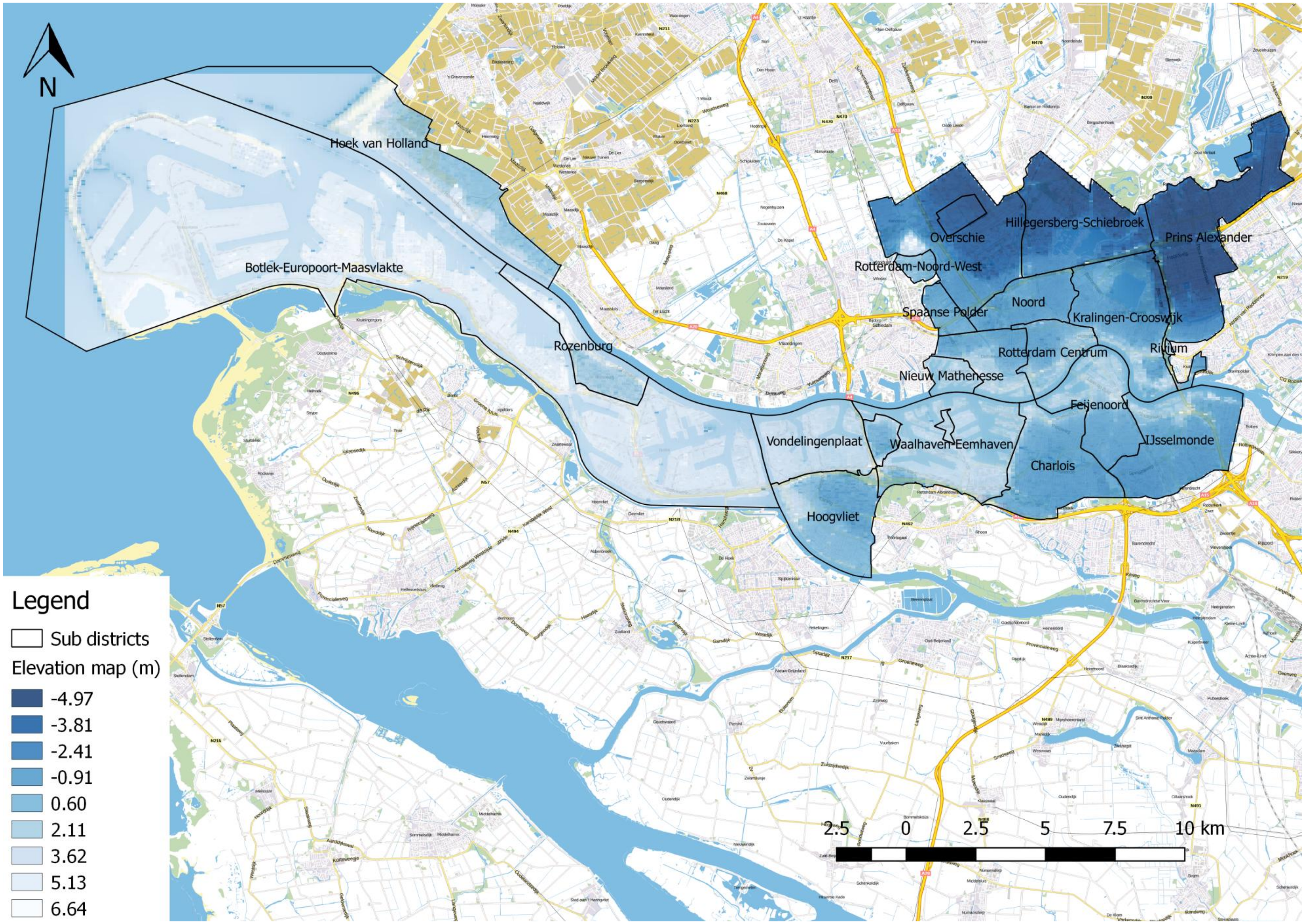

Figure 37: Elevation map of Municipality Rotterdam

Appendix C: Company-value matrix

Potential consequences for company values — **Occurrence frequency**

	Availability					Safety	Environment/Health		Living space quality	Reputation	Law & regulations	Economy	Almost impossible <0,003/yr	Rare 0,003 - 0,03 /yr	Incidental 0,03 - 0,3 /yr	Yearly 0,3 - 3 /yr	Monthly 3 - 30 /yr	Weekly >30 /yr
Extreme	Main flood defense out of order in storm season > 100 days	Network chain not available >5.000.000 user days	N.A.	N.A.	N.A.	Multiple deaths	Overflow dry condition > 5.000 m3.	Overflow rainfall condition > 365.000 m3.	Water nuisance on the street >2500 user days	Councilor resignation	Conviction	>I 10.000.000,-	M	H	VH	E	E	E
Severe	Secondary flood defense out of order in storm season > 100 days	Network chain not available 500.000 - 5.000.000 user days	N.A.	N.A.	N.A.	One death, permanent injury/handicapped	Overflow dry condition 500 - 5.000 m3.	Overflow rainfall condition 36.500 - 365.000 m3.	Water nuisance on the street 250 - 2500 user days	Councilor reprimanded	Lawsuit	I 1.000.000,- - I 10.000.000,-	L	M	H	VH	E	E
Proper	Secondary flood defense out of order in storm season 10 - 100 days Obstruction commercial shipping >1000 user days	Network chain not available 50.000 - 500.000 user days	N.A.	Public green space not available >100.000 user days	N.A.	Severely wounded	Overflow dry condition 50 - 500 m3.	Overflow rainfall condition 3.650 - 36.500m3.	Water nuisance on the street 25 - 250 user days	Questions from the board	Court order	I 100.000,- - I 1.000.000,-	S	L	M	H	VH	E
Moderate	Secondary flood defense out of order in storm season 1 - 10 days Obstruction commercial shipping 100-1000 user days	Network chain not available 5.000 - 50.000 user days	Public lighting not available > 1000 user days, along a road or bicycle path	Public green space not available groenvoorziening 10.000 - 100.000 user days	Play facilities not available >10.000 user days	Wounded and absenteeism	Overflow dry condition 5 - 50 m3.	Overflow rainfall condition 365 - 3.650 m3.	Water nuisance on the street 2.5 - 25 user days	Lots of negative publicity	Arrangement	I 10.000- - I 100.000,-	S	S	L	M	H	VH
Small	Floodgate commercial shipping out of order 1 - 10 days Obstruction commercial shipping 10 - 100 user days	Network chain not available 500 - 5000 user days	Public lighting not available 100 - 1000 user days, along a road or bicycle path	Public green space not available 1000 - 10,000 user days	Play facilities not available 1000 - 10,000 user days	Near accident	Overflow dry condition 0,5 - 5 m3.	Overflow rainfall condition 35 - 365 m3.	Water nuisance on the street 0.25 - 2.5 user days	Negative publicity	Fine	I 1.000,- - I 10.000,-	S	S	S	L	M	H
Very small	Floodgate commercial shipping out of order 1 day Obstruction commercial shipping <10 user days	Network chain not available < 500 user days	Public lighting not available 10 - 100 user days, along a road or bicycle path	Openbare groenvoorziening Public green space not available < 1000 user days	Play facilities not available <1000 user days	Dangerous situation	Overflow dry condition < 0,5 m3.	Overflow rainfall condition < 35 m3.	Water nuisance on the street < 0.25 user days	Small publicity	Warning	< I 1.000,-	S	S	S	S	L	M

Figure 43: Company-value matrix