Technische Universiteit Delft

Quantifying flood damage

A case-study in Kumasi, Ghana

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by

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Preface

This thesis is written as partial fulfillment of the requirements for the degree of Bachelor of Science in Civil Engineering at the Delft University of Technology. The research is performed at the Water Resources group within the Water management Department.

As of around one and a half year ago, I got to the realisation of my interest in extreme rainfall and the effects on urban areas. This realisation came as I walk around the city of Rotterdam and saw water squares integrated in the infrastructure. During heavy rainfall, these square function as temporary storage of the rainwater and during sunny days the squares can be used as playgrounds for kids.

This seamless type of integration of solution into the existing infrastructure without people noticing got me thinking. Climate change will result in more extreme rainfall in the future, and whereas the Netherlands has the financial resources to fix the problems related to this, developing countries will have much more difficulties fighting the results of climate change.

With the knowledge we have at Delft University of Technology we are of great value for developing countries by supporting with engineering solutions. With this research, I hope to have made a contribution to the reduction of flood damage in Kumasi and I hope that the results of this research can help to show the urge of precocious measures against floods.

Unfortunately my field trip to Kumasi could not take place because of the COVID-19 outbreak, but nevertheless I am satisfied with this research. I do hope that I will have the opportunity to visit Kumasi in the future to see what the city looks like and to see the effects of the floods in real life.

I would like to thank Marie-Claire ten Veldhuis and Nick van de Giesen for being my supervisors and introducing me to the project. When the plans for going to Kumasi were almost complete and corona struck they were very flexible and helped me change the project in such a way that the analyses could still be performed from Delft. Most of the preparatory work was therefore not done for nothing.

G.C.M. Wiersma
Delft, June 2020

Abstract

In this research, the flood damage caused by heavy rain and plastic blockage in the neighbourhood of Atonsu, Kumasi is quantified. Rapid urbanisation and poor waste management result in floods with an increasing impact in Kumasi, the fastest growing city of Ghana. This rapid growth of the city results in uncontrolled urbanisation of the floodplains and induces damage to homes during a flood event. Furthermore, due to a poor waste management system around thirty percent of the waste produced in Kumasi gets dumped in the streets and forms blockage of the water flow in the river. Moreover, the river is used as a dump not only by citizens but also by factories, which results in contaminated river water. As this research aims to give a first insight into the actual flood damage in Kumasi, simplified methods are applied, as they do not require a lot of data. To quantify the tangible damage, expressed in monetary values, depth-damage curves are constructed for different types of land use in the study area, to show the relation between the inundation depth or inundated area and the monetary damage. Besides that the intangible damage is quantified in the form of the number of lives lost and people exposed to waterborne diseases, both depending on the total number of people affected. The damage is quantified for floods induced by four different rain events, all with different peak precipitation, duration and frequency. The results indicate that the larger the rain event, the more damage it causes. It is furthermore estimated that plastic blockage of the flow of the river results in an increase of monetary damage of up to 5.7 percent and the number of people that are affected by the flood increases with up to 17.4 percent. Finally, the results of this research show the magnitude of flood damage in Kumasi and could be used to show the urge of measures that need to be taken to reduce the flood damage.

Contents

1

Introduction

Floods form an increasing risk for urban areas in developing countries, with damage to homes, loss of life and disease outbreaks as consequences (Ansah et al., 2020, Mearns and Norton, 2010). In contrary to general belief that climate change is the main reason for an increasing amount of floods, previous research has shown that anthropogenic factors, in particular urbanisation, have a great impact on urban floods (Korah and Cobbinah, 2016). Kumasi is the fastest growing city in Ghana, with over two million inhabitants already, and facing at least four floods annually (Amoateng et al., 2018). During a recent flood, in September 2019, seven children lost their lives in Kumasi (GhanaWeb, 2019), showing the importance of a solution to reduce the impact of floods. Two reasons for these flood events are the growth of Kumasi, resulting in uncontrolled urbanisation of the green areas in the city, and plastic waste in the rivers due to poor waste management. Furthermore, the poor quality of the river water might result in outbreaks of waterborne diseases during floods.

1.1. Background

Ghana is a country on the west coast of Africa, located close to the equator and having a tropical climate (Weather&Climate, 2020). Kumasi is, with over two million citizens, the second-largest city in Ghana and the number of inhabitants is expected to keep growing in the future (Ritchie and Roser, 2020). Kumasi is the capital city of the Ashanti region, located in the south-west of Ghana. The city has a tropical climate with a dry season from December to February and a long wet season from March to November. 90 percent of the annual 1397 mm of precipitation falls during heavy rain events in the wet season, with June being the month with the rainiest days as well as the most precipitation (WeatherAtlas, 2020).

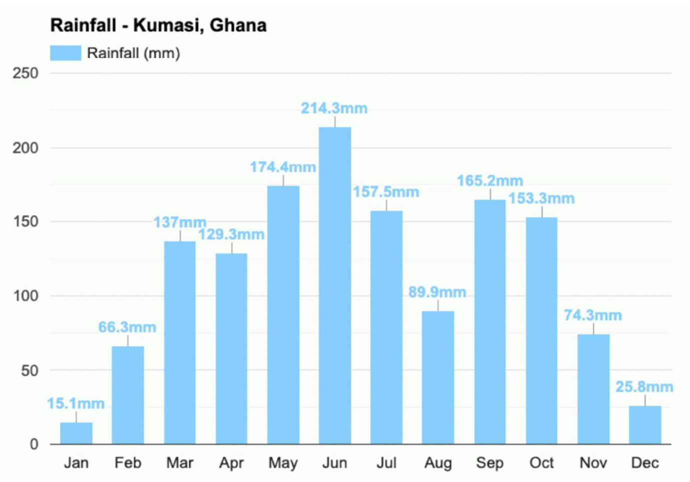


Figure 1.1: Average monthly rainfall in Kumasi (WeatherAtlas, 2020)

1.1.1. Urbanisation

Worldwide the amount of people living in cities is rapidly growing. This is seen in Ghana as well, where more than half of the population is living in cities nowadays, compared to only 31 percent in 1980 (Ritchie and Roser, 2020). This number is expected to keep growing in the future, which could result in more challenges. The rapid growth of Kumasi resulted in uncontrolled urbanisation of the floodplains, causing a decrease in green area and rivers in the city as can be seen in figure 1.2 (Tockner et al., 2008).

The floodplains, or wetlands, are considered no man's land by the people and therefore these areas are a cheap location to build a house (Campion and Owusu-Boateng, 2013). Poor administration and management of these floodplains by the authorities make it possible for people to build houses without getting permission.

It has been calculated that the area of rivers and floodplains was reduced by 83 percent between 1985 and 2013 (Amoateng, 2016). Due to the reduction of river area the rainwater needs to be drained by a network with a smaller capacity, which makes it more vulnerable to overflow during heavy rain.

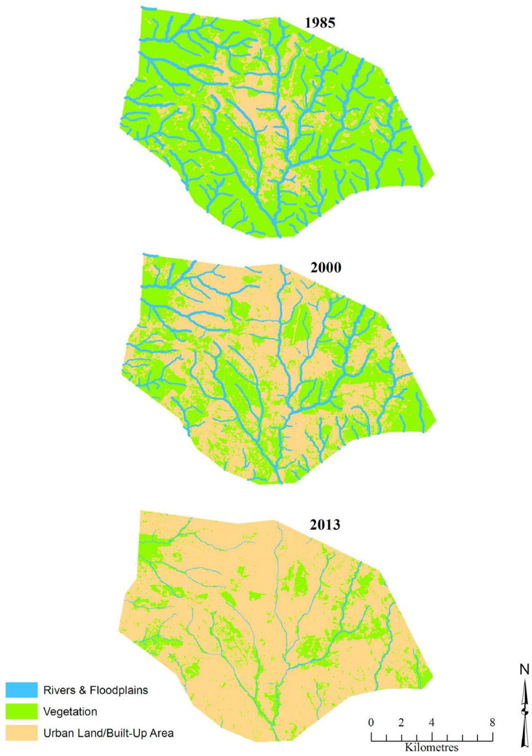


Figure 1.2: Reduction of rivers in Kumasi between 1985 and 2013 (Amoateng, 2016)

1.1.2. Plastic waste

According to the Dutch Ministry of Foreign Affairs, 73 million kilos of PET bottles are dumped into the environment every year in Ghana. Only two percent of the PET plastics are recycled because the raw materials to produce PET are as cheap as the cost of recycled plastics (Keesman, 2019). The growing economy and population resulted in an increase in the use of plastic, and therefore in an increase in plastic waste in the city of Kumasi (Owusu-Sekyere et al., 2013).

Ghanaian citizens have to pay waste fees in order to have their waste collected, resulting in rich neighbourhoods having door to door waste collection and poor neighbourhoods having only communal containers to take their waste to (Keesman, 2019). As a result around 30 percent of the produced waste in Kumasi gets dumped on the street, in other public areas and in the rivers (Ketibuah et al., 2020, Othchere et al., 2014). This altogether results in plastic waste clogging in the rivers of Kumasi, blocking the flow and making the city more vulnerable to floods.

1.1.3. Water quality

The rivers in Kumasi are used as a dump for untreated wastewater from factories and as a sewer for many households (Obiri-Danso et al., 2005). The quality of the river water in Kumasi is very poor, containing too high concentrations of, amongst others, nitrogen, phosphorous, cholera and e-coli bacteria (Gyamfi et al., 2013). Being in contact with the contaminated water could lead to waterborne diseases, such as diarrhoea and cholera, and result in death. Flooding of the river increases the number of people being in contact with the contaminated water and thus increases the possibility of waterborne disease outbreaks.

1.1.4. Quantitative flood risk analysis

According to LGA (2020) flood risk is "a combination of the probability of an event happening and the consequences if it occurred", where the most common division of the consequences is in tangible and intangible damage, with tangible damage being all the damage that can be expressed in monetary values and intangible damage everything else. These damages could furthermore be subdivided into direct damage, from direct contact with the water, and indirect damage, occurring not during the event, but afterwards (Scorzini and Frank, 2017).

Methods used to quantify tangible and intangible flood damage differ due to the variability of data available in different areas. The best estimates can be made using a multi-variable flood damage model, which requires large data sets (Wagenaar et al., 2017). A more simplified method to quantify flood damage is to use depth-damage curves, which only requires inundation depths in the area (Huizinga et al., 2017). The downside to this method, however, is that it is not very accurate, with a correlation coefficient between the inundation depth and the damage of below 0.5 (Wagenaar et al., 2017). Nevertheless, depth-damage curves can give a valuable, first rough flood damage estimation for developing countries with scarce available data (Komi et al., 2016).

1.2. Problem statement

The rapid population increase of Kumasi is leading to reduction of the river area, uncontrolled urbanisation of the floodplains and an increase of waste. Together with a poor waste management system and river water quality, this is the perfect recipe to cause a lot of damage during floods.

In previous research the contribution of heavy rainfall and plastic blockage to flood events in Kumasi have been analysed (Tjia, 2020). The next step is to turn these analyses into a quantitative flood risk analysis, for which an estimation of the associated flood damage is needed.

1.3. Scope

This research will focus on estimating flood damage associated with flood events caused by heavy rainfall and plastic blockage. The research will be done for Kumasi, Ghana. More specifically, the neighbourhood of Atonsu is taken as the study area, as previous research used for this analysis has also been done for this specific neighbourhood (Tjia, 2020). Atonsu is a neighbourhood in the south-west of Kumasi with over 65,000 inhabitants (GSS, 2014).

In this research the flood damage will be quantified for both scenarios with and without plastic waste interference of the flow of the river. The results of the previous research consist of maps with different inundation depths for different flood events. These same depth classes will also be used in this research. The depth classes are:

- 0.20 m (average of 0.10 - 0.30 m)
- 0.40 m (average of 0.30 - 0.50 m)
- 0.75 m (average of 0.50 - 1.00 m)
- 1.25 m (average of 1.00 - 1.50 m)
- 1.75 m (average of 1.50 - 2.00 m)
- > 2.00 m

Figure 1.3: Study area

1.4. Research questions

The research will be done by answering the following question:

What is the quantitative flood damage associated with flood events caused by heavy rainfall and plastic blockage in the neighbourhood of Atonsu in Kumasi, Ghana?

Which is divided into the following sub-questions:

1. *How can flood damage be quantified?*
2. *What is the influence of plastic blockage on the quantitative flood damage?*
3. *Who is affected by and would benefit from reduced flood damage?*

1.5. Report structure

Chapter 2, Methodology, explains the methods used to quantify the flood damage, as well as the theory behind these methods. Chapter 3 gives and explains the results of the quantitative flood analysis for different flood events in Atonsu. Finally, in chapter 4, the conclusion and recommendations for future research will conclude this research.

2

Methodology

To quantify the total flood damage, a distinction between tangible and intangible damage is made. Tangible damage contains all the damage that can be translated into monetary values, such as damage to properties and business. Intangible damage cannot be expressed in monetary values. Examples of intangible damage are loss of life, negative impact on human life, health-related issues and impact on the environment (Hammond et al., 2013). The tangible damage is quantified using the different flood depths, whereas intangible damage is quantified using the inundated area per flood event. The entire process of quantification is schematised in figure 2.1.

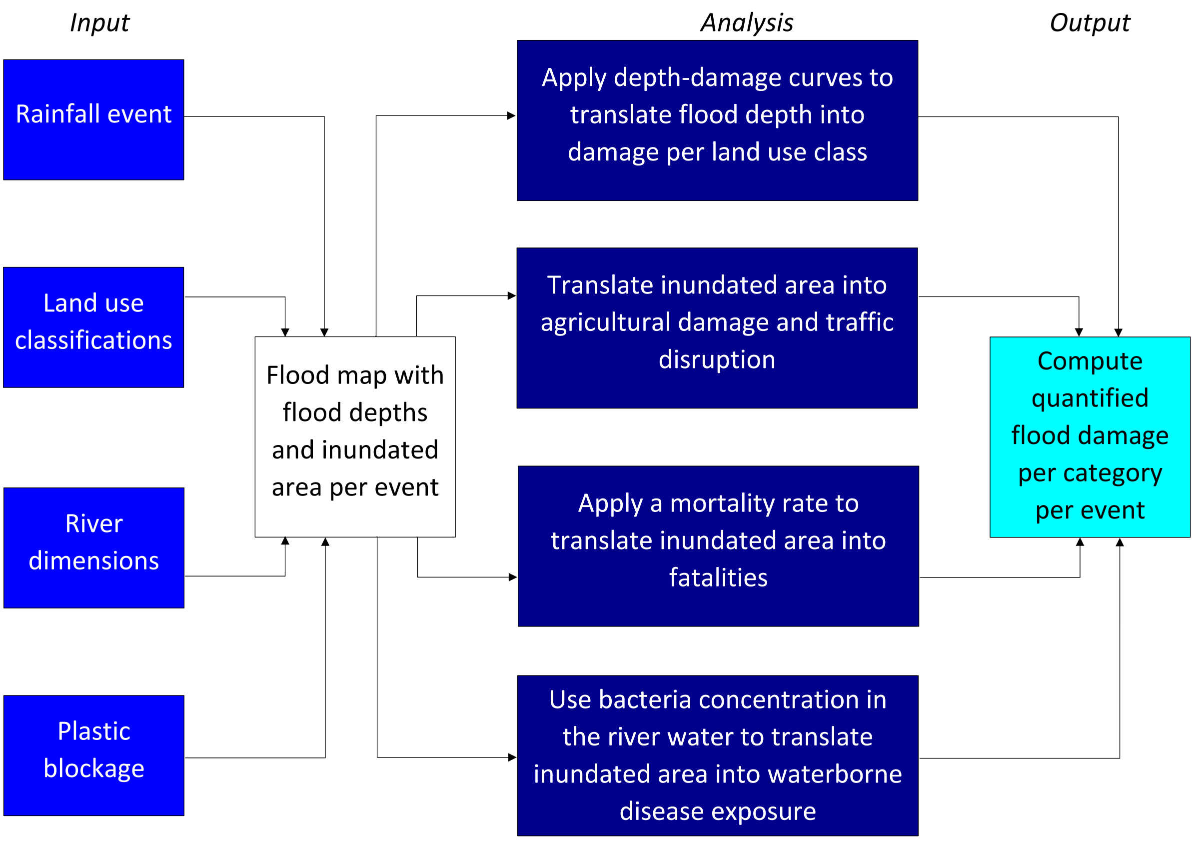


Figure 2.1: Process scheme of the quantification of flood damage

2.1. Land use classification

For the damage quantification, the study area is divided into different classes of land use:

- Residential buildings
- Commercial buildings
- Agriculture
- Traffic
- Infrastructure

There are different types of residential building in the study area. For quantification these are divided into stone houses and self-made houses. Stone houses have a foundation, walls and a roof, whereas self-made houses often do not have a foundation and are made of corrugated iron and wood. Figure 2.2 shows the difference between a stone and a self-made house.

Figure 2.2: houses in Atonsu, Kumasi (Tjia, 2019)

(a) Stone house (b) Self-made house

There are also different types of commercial buildings in the study area. These are divided into shops and stalls. Shops are official stores and stalls are self-made stands on the street where products are sold. Figure 2.3 shows the difference between a shop and a stall.

Figure 2.3: Commercial buildings in Atonsu, Kumasi (Google Streetview, 2020)

(a) Shops (b) Stalls

This land use classification, with a subdivision of residential and commercial buildings into stone houses, self-made houses, shops and stalls, is presented in a map of the study area in figure 2.4. Figure 2.4 is made using QGIS, a free and open source geographic information system. In this program Google Satellite images are used to locate the different buildings.

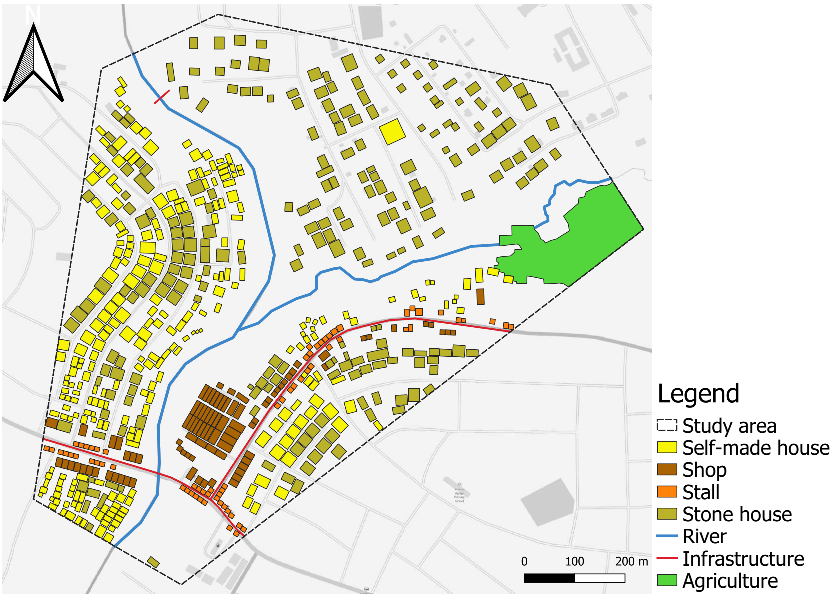


Figure 2.4: Land use classification map

2.2. Rain events

For the quantification of flood damage in Kumasi, four different rain events that have been modelled by Tjia (2020) are used. The four events with their precipitation and duration are shown in table 2.1. There are two bridges in the study area, shown with the red lines crossing the river in figure 2.4. To run different scenarios for each rain event, these bridges are both once blocked for 33 percent and once for 67 percent. This will simulate the effect of plastic blockage on the flow of the water and on the total flood damage. For all of these scenarios flood maps have been created by Tjia (2020), which are combined with figure 2.4 to form specific flood maps that are used to quantify the flood damage per scenario in chapter 3.1.

	Date	Duration [h]	Total Precipitation [mm]	Hourly precipitation [mm]	Peak precipitation [mm]
Event 1	23/05/2019	4	27	6.75	22
Event 2	19/09/2017	3	57	19	56
Event 3	22/06/2019	6	83	13.83	60
Event 4	28/06/2018	9	103	11.44	78

Table 2.1: Rain event used to quantify flood damage (Tjia, 2020)

Furthermore, Tjia (2020) calculated the frequency of occurrence of rain events with a certain peak precipitation. From this we can infer that the yearly average frequency of downpour similar to or larger than event 1 is 31.7. For event 2 this is 3, for event 3 this is $\frac{1}{3}$ and for event 4 the yearly average frequency is also $\frac{1}{3}$. With these numbers and the quantified damage per event a risk analysis can be performed to calculate the risk for each event, where $risk = frequency \cdot consequence$.

2.3. Tangible damage

The land use classes all have different quantified damage values for the different inundation depths. For each class the relation between the flood depth and the quantified damage value is set, this is done with depth-damage curves.

2.3.1. Depth-damage curves

Depth-damage curves show the relation between inundation depth and damage. They are used to translate a flood depth into a monetary damage value. For every land use class a different depth-damage curve is needed. From these curves the total quantified tangible flood damage can be calculated.

Residential buildings

For residential buildings, the total damage is divided into structural and furniture damage. The maximum structural damage value of a stone house is estimated to be roughly three times the monthly rental price of a double room apartment in the flood sensitive areas of Kumasi, which is equal to around 450 Ghanaina Cedi (GHS) (Attakora-Amaniampong et al., 2016). Furthermore the maximum structural damage value for a self-made house is estimated to be five times the monthly rent of a single room apartment in the flood prone areas of Kumasi, which is equal to 100 GHS (Attakora-Amaniampong et al., 2016). The maximum damage value of furniture damage for a stone house is taken to be equal to one month of rent of a double room apartment, which equals 150 GHS. At last, the maximum furniture damage of a self-made house is taken to be equal to three months of rent of a single room apartment, which is 60 GHS.

The damage factors from which the depth-damage curves for both stone and self-made houses have been constructed are estimated based on the percentage of the maximum damage. As stone houses are built on a foundation, low inundation depths of 0.2 meters will not cause any damage to the structure nor to the furniture, whereas self-made houses are not built on an elevation and will experience damage with a flood depth of 0.2 meters. As the inundation depth grows, the damage factors for both structural and furniture damage also grow, up to a maximum for structural damage at a maximum flood depth of 2.00 meters. The maximum damage factor for furniture damage is already estimated to be reached at an inundation depth of 1.75 meters, as at this depth all the furniture in any house needs to be either replaced or thoroughly cleaned. The exact explanations and calculations for constructing the depth-damage curves for stone and self-made houses can be found in appendices A.1 and A.2. The final depth-damage curve for a stone house can be found in figure 2.5 and the final depth-damage curve for a self-made house can be found in figure 2.6. These final depth-damage curves will be used for the quantification of flood damage to residential buildings for every flood event.

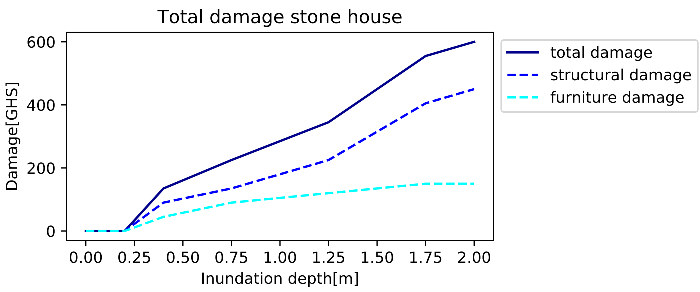


Figure 2.5: Monetary depth-damage curve stone house

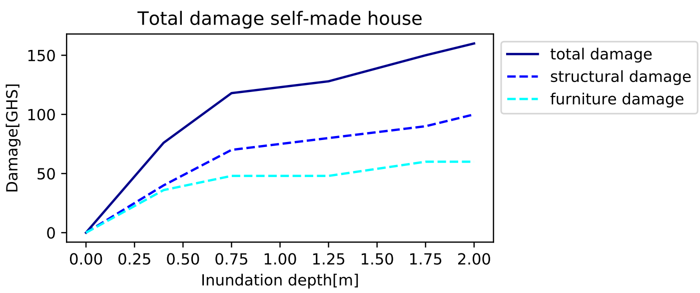


Figure 2.6: Monetary depth-damage curve self-made house

Commercial buildings

For commercial buildings the total damage is divided into structural and inventory damage. The maximum structural damage value for a shop is estimated to be equal to two months of rent of a double room apartment in the flood prone areas in Kumasi. This is equal to 300 GHS (Attakora-Amaniampong et al., 2016). The maximum damage value for a stall is taken to be equal to the maximum damage value of a self-made house, which is 100 GHS. The maximum damage value to the inventory of both a shop and a stall is taken to be twice the maximum structural damage value. So, for a shop the maximum inventory damage value is 600 GHS and for a stall this is 200 GHS.

The damage factors for structural damage of a shop are taken to be equal to the damage factors for structural damage of a stone house, as the structures of these buildings are very similar in general. The structural damage factors for a stall are based on the appearance of the average stall, which is usually built as shown in figure 2.3b. The inventory of a shop is estimated to be equally distributed from the floor of the shop at 0.3 meters up to the ceiling at 2.00 meters. Half of the inventory of a stall is taken to be on the shelves at 0.5 meters and the other half is estimated to be equally divided between 0.5 and 2.00 meters. More thorough explanations and calculations for constructing the depth-damage curve for shops and stalls can be found in appendices A.3 and A.4. The final depth-damage curve of a shop is as shown in figure 2.7 and the final depth-damage curve for a stall is given in figure 2.8. These final depth-damages are used for the quantification of flood damage to commercial building for every flood event.

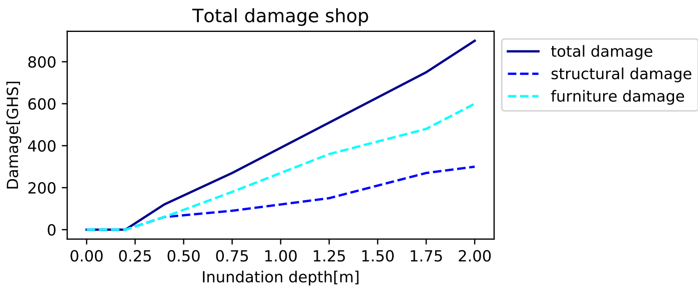


Figure 2.7: Monetary depth-damage curve shop

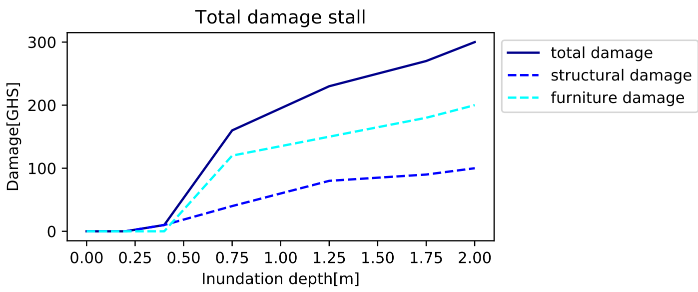


Figure 2.8: Monetary depth-damage curve stall

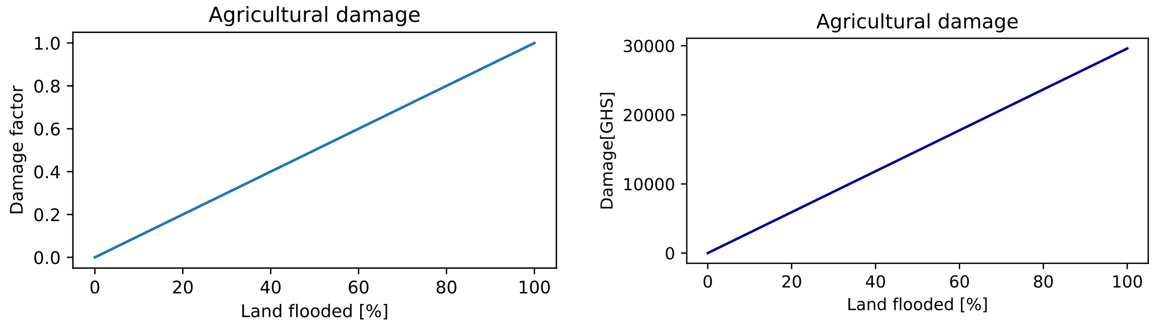
Agriculture

There are ten different farmer cooperatives with land in the Atonsu area, of which two lose around 80 percent of their income during the average flood and the other eight lose around twenty percent of their income (Anobil, 2020). Out of these ten farmer cooperatives there are two with land in the study area, namely Peace and Love Vegetable Growers Association and Opoku Sika farmers (Anobil, 2020). The maximum loss of the farmers is around 4000 GHs per acre (Anobil, 2020). The agricultural area in the study area is 7.4 acres, which means that the maximum agricultural damage is $7.4 \cdot 4000 = 29,600$ GHS.

All the land that floods, no matter the inundation depth, is unusable for agriculture that same year and all the crops grown on it will be destroyed. Therefore, the damage curve for agriculture will not be a depth-damage curve, but an area-damage curve, with the area in percentage of the total farmland area in the study area. The maximum damage value is equal to the financial loss for the farmers when the entire farmland area is flooded, which is equal to the maximum total income of the two farmer cooperatives combined, 29,600 GHS.

The damage curve is linear because with an extending inundated area the loss of income grown linearly. The normalised damage curve for agriculture can found found in figure 2.9a. Multiplying this normalised damage curve with the maximum damage value gives the monetary damage curve that is used for quantification of flood damage for every flood event. This curve can be found in figure 2.9b.

Figure 2.9: Damage curves for agricultural damage



(a) Normalised damage curve

(b) Monetary damage curve

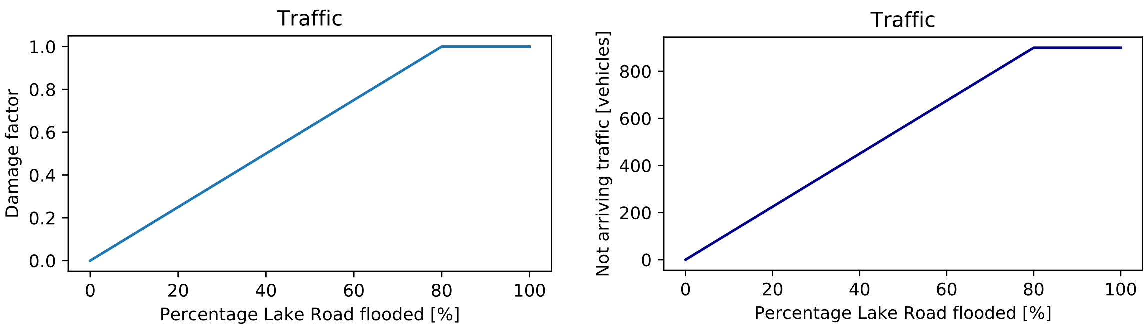
Traffic

The majority of the roads in the study area are sand roads, with the exception of Lake Road, a two lane asphalt road crossing the river in the south of the study area, as shown with the red line in figure 2.4. Lake Road is the major road through the study area and an important connection between the city centre of Kumasi and the neighbourhood Esreso and Lake Bosumtwi (Owusu-Ansah and O'Connor, 2008). Disruption of the traffic in Lake Road will therefore result in many people not being able to reach their destination. There are no traffic count data of Lake Road, therefore the average traffic density is estimated to be equal to the capacity of a two lane, two way road with free frontage access, parked vehicles and heavy cross traffic, which is 900 vehicles per hour (Ind, 1990). This number is the recommended design capacity for this type of roads in India, but as India and Ghana are both developing countries and the description meets what Lake Road looks like, 900 vehicles per hour is a representative number.

Driving through water is dangerous and according to TheAA (2020), one should not drive through water deeper than ten centimeters. This makes all the inundation depths used in this research to be too deep to drive through. Therefore, similar to what has been done for agriculture, the damage curve will be an area-damage curve, based on the percentage of Lake Road flooded. As the traffic density is measured in vehicles per hour, the flood duration is also an important parameter in quantifying the damage. Therefore the calculated number of vehicles per hour will be multiplied by the flood duration for every single flood.

When Lake Road is entirely flooded it is not possible for any traffic to use the road, giving a damage factor of 1. When the road is flooded for 80 percent, the damage factor will also be 1 as the not flooded part of the road is too small to drive on. When the road is flooded for 40 percent, it is only usable as a single lane road, reducing the capacity with 50 percent, corresponding with a damage factor of 0.5. When the road is flooded for 20 percent, reduction of speed will ensure the road is still usable as a two-lane road. Reducing the speed will cause an estimated 25 percent reduction in capacity and so the damage factor is 0.2. For a 60 percent flooded road, reduction in speed will ensure the road is still usable as a single lane road. The combination of changing from two lanes to one and having a speed reduction causes an estimated 75 percent reduction in capacity, giving a damage factor of 0.75. These percentages of flooded area and their corresponding damage factors together form the damage curve shown in figure 2.10a. By multiplying this normalised curve by the maximum estimated traffic density, 900 vehicles per hour, we get the quantified damage curve for traffic disruption, as shown in figure 2.10b. This curve is used to quantify the traffic disruption for every flood event.

Figure 2.10: Damage curves for traffic delays



(a) Normalised damage curve

(b) Quantified damage curve

Infrastructure

None of the roads, not the sand roads, nor the asphalt roads, get repaired after being flooded (Annor, 2020). This results in no costs concerning any road. Furthermore there are two bridges crossing the river in the study area. Rising water levels will cause larger force on the bridges, which could result in collapse of the bridge. Several bridges in Kumasi have already collapsed in the past due to floods (GhanaWeb, 2017). However, the average bridge these days is built to survive all flood except for extreme floods that happen once every 200 years (BBCNews, 2009). This means that for every bridge there is a yearly 0.5 percent chance of collapsing. One could argue that the bridges in Kumasi are not the global average and will most likely have a higher chance of collapsing, but due to the small chance and unknown cost of building a new bridge, this is also not taken into account in the quantification of flood damage. This results in infrastructure not contributing to the flood damage for this research.

2.4. Intangible damage

The intangible damage contains all damage that cannot be expressed in monetary values. For this research two types of intangible damage are estimated, namely the loss of life and the number of people that risk getting waterborne diseases. Intangible damage is difficult to quantify, because there are no direct values to be linked to a persons life. Therefore the quantification of intangible flood damage is more subjective (Lekuthai and Vongvisessomjai, 2001).

For both the loss of life and the amount of people getting waterborne diseases it is important to know the number of people affected [PA] by a single flood event. This number is found by multiplying the amount of houses flooded [HF] during a flood event, no matter the inundation depth, by the average number of people living in one house [PPH], as can be seen in equation 2.1. The average number of people living in one house in Atonsu is estimated to be eleven (GSS, 2014). The total number of people affected will also be used as a separate parameter for the total quantified flood damage. This is because this number is more straight forward to estimate and less prone to errors compared to the loss of life and the amount of people getting waterborne diseases.

$$PA = HF \cdot PPH \tag{2.1}$$

2.4.1. Loss of life

The number of lives lost for every scenario is calculated using a mortality rate. This mortality rate is the number of fatalities [FAT] divided by the total number of people affected [PA] (Jonkman, 2005).

With data of historical flood event in Ghana, which can be found in appendix B, the mortality rate for Atonsu is estimated to be 0.0002. The number of fatalities for each scenario can now be calculated using equation 2.2.

$$FAT = 0.0002 \cdot PA \tag{2.2}$$

2.4.2. Waterborne diseases

The number of people exposed to bacteria causing waterborne diseases is taken to be the same as the total number of people affected by a flood event. This is because water flooding into a house will result in the people living in the house getting in contact with the water and thus being exposed to the bacteria in the water. The rivers in Atonsu contain cholera (Osei et al., 2010) and high concentrations of faecal coliform E-coli bacteria (Obiri-Danso et al., 2005), which can both cause severe diarrhoea (Rivera et al., 2001). In fact, according to the WHO (2018), E-coli is fatal for three to five percent of the people suffering from it and cholera could result in death if not treated for ten percent of the people suffering from it (CDC, 2020).

The maximum accepable concentration of E-coli bacteria in the water is 126 MPN per 100 ml (USEPA, 2003), while the measured concentration of E-coli in the river water in Kumasi is $7.8 \cdot 10^{10}$ MPN per 100 ml (Obiri-Danso et al., 2005). For cholera the exact concentrations in the river water are unknown, so this will not be taken into consideration for the calculations.

To estimate the number of people exposed to waterborne diseases, a dilution rate [d_{rate}] for every event should be calculated to know the concentration of bacteria in the flood water [C_{flood}]. This concentration in the flood water is calculated by multiplying the dilution rate with the bacteria concentration of the dry weather flow [C_{DWF}], as shown in equation 2.3.

$$C_{flood} = d_{rate} \cdot C_{DWF} \tag{2.3}$$

To calculate the dilution rate we need to know the dry weather flow of the river as well as the increase of the flow due to the falling rain. The velocity [u] of the main river in dry weather conditions is 0.54 m/s, with the water depth [h] being 0.3 m and a width [w]of the river of 26 m (Tjia, 2020). The dry weather flow [Q_{DWF}] is calculated using equation 2.4, where $A = h \cdot w$ is the cross-sectional area of the river. This gives a dry weather flow of the river of $2.8 m^3/s$.

$$Q_{DWF} = A \cdot u \tag{2.4}$$

The increase of the flow due to the falling rain [ΔQ] is equal to the total area of the catchment of the river, which is $111.4 \cdot 10^6 m^2$ (Tjia, 2020) multiplied by the amount of rain falling during the specific event per hour [p_h], as shown in equation 2.5.

$$\Delta Q = 111.4 \cdot 10^6 \cdot p_h \tag{2.5}$$

As the hourly precipitations of all the events are known and given in table 2.1, the ΔQ can be calculated for every event. From the increase of the flow the dilution rate for every event can be calculated using equation 2.6. All of the corresponding values are given in table 2.2.

$$d_{rate} = \frac{Q_{DWF}}{Q_{DWF} + \Delta Q} \tag{2.6}$$

	Hourly precipitation [mm]	**Hourly precipitation [m]**	**Increase flow [m^3/h]**	**Increase flow [m^3/s]**	**Dilution rate**
Event 1	6.75	$6.75 \cdot 10^{-3}$	417750	116	0.024
Event 2	19	$19 \cdot 10^{-3}$	2116600	588	0.005
Event 3	13.83	$13.83 \cdot 10^{-3}$	1537320	427	0.007
Event 4	11.44	$11.44 \cdot 10^{-3}$	1269960	353	0.008

Table 2.2: Increase of the flow due to the different rain events

With the dilution rate and the dry weather concentration of the bacteria in the river water, the bacteria concentration of E-coli bacteria in the floodwater can be calculated using equation 2.3. This a bacteria concentration for event 1 of $18.7 \cdot 10^8$ MPN per 100 ml, for event 2 of $3.9 \cdot 10^8$ MPN per 100 ml, for event 3 of $5.46 \cdot 10^8$ MPN per 100 ml, and for event 4 of $6.24 \cdot 10^8$ MPN per 100 ml. All of these concentrations exceed the accepted number of 126 MPN per 100 ml and therefore all people affected by a flood will be exposed to E-coli bacteria and risk being infected.

3

Results and discussion

3.1. Results

In this chapter the results of the quantification of the flood damage for the four modelled rain events in Kumasi are presented. For all four events the total damage is estimated without plastic blockage in the river and the total risk of every event is given. Next, for event 1 the scenario without plastic is compared with the scenario with bridge 1 blocked for 67 percent to see the influence of plastic waste blockage in the river on the flood damage. Furthermore the assumptions and uncertainties of this research are discussed.

3.1.1. Event 1

Tangible damage

During flood event 1 a total of thirteen stone houses flood, with different inundation depths and a total damage of 4530 GHS. Besides that ten self-made houses flood with a total damage of 760 GHS. Three shops flood during flood event 1, resulting in a damage of 270 GHS and seven stalls flood, giving a damage of 1170 GHS. Furhtermore the 25 percent of the agricultural land floods, which gives a damage of $0.25 \cdot 29,600 = 7400$ GHS. This results in a total monetary damage for rain event 1 of 14,130 GHS.

As can be seen in figure 3.1 Lake Road is flooded across the width and therefore no traffic is able to make use of the road for as long as the rain lasts,which is four hours. As the damage for an entirely flooded Lake Road is 900 vehicles per hour, the total amount of vehicles not arriving at their destination is $4 \cdot 900 = 3600$.

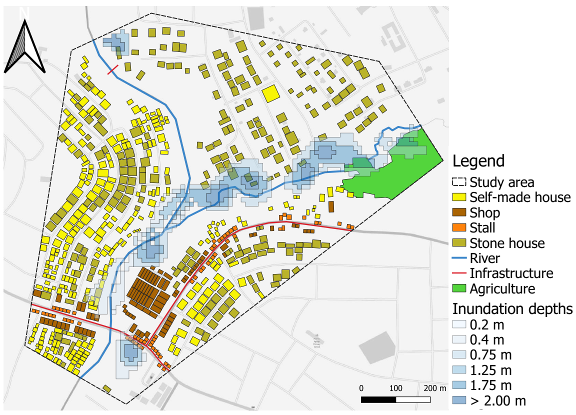


Figure 3.1: Flood map event 1

Intangible damage

As thirteen stone houses and ten self-made houses flood, the total amount of houses flooded is 23. Multiplying this with the average number of people living in one house gives a total of $23 \cdot 11 = 253$ people affected. With 0.0002 as the mortality rate, 0.05 lives are lost during event 1. Furthermore all 253 people affected risk getting diarrhoea through the E-coli in the water.

Risk analysis

As mentioned in section 2.2 the yearly average frequency of a rain event with a magnitude equal to or larger than event 1 is 31.7. This means that on average a rain event larger than or similar to event 1 or larger occur 31.7 times every year. This gives a total estimated yearly damage of $31.7 \cdot 14,130 = 447,921$ GHS. Furthermore it results in $31.7 \cdot 900 = 28,530$ vehicles not arriving at their destination annually. $31.7 \cdot 253 = 8020$ people will be affected by floods and risking getting diarrhoea and $31.7 \cdot 0.05 = 1.6$ lives are lost yearly.

3.1.2. Event 2

Tangible damage

A total of 39 stone houses flood during event 2, resulting in a total damage of 9,000 GHS. There are 31 houses that flood which gives a total damage of 2306 GHS. Furthermore ten shops and ten stalls flood during rain event 2, resulting in 1,410 GHS and 1,960 GHS damage. Figure 3.2 shows that forty percent of the agricultural land floods, which gives a total agricultural damage of 11,840 GHS. Altogether this results is a total monetary flood damage due to rain event 2 of 26,516 GHS.

Besides that, just like with event 1, Lake Road is flooded across the entire width as can be seen in figure 3.2. Rain event 2 lasts for three hours, which results in $3 \cdot 900 = 2700$ vehicles not arriving on their destination due to the flood.

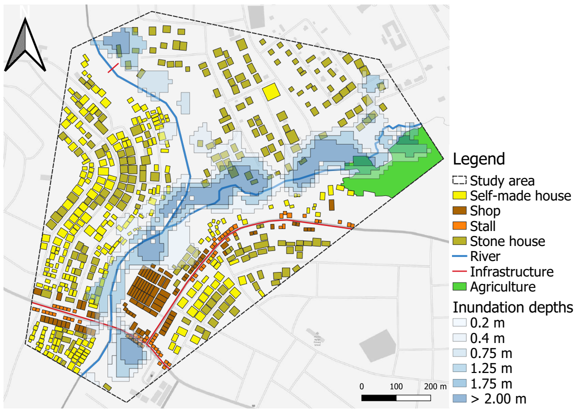


Figure 3.2: Flood map event 2

Intangible damage

The 39 stone and 31 self-made houses make a total of 70 houses that flood during event 2. This gives $70 \cdot 11 = 770$ people that are affected in total, which all risk being infected by E-coli bacteria in the water and getting diarhhoea. From this number we can calculate that $0.0002 \cdot 770 = 0.15$ lives are lost due to the flood caused by rain event 2.

Risk analysis

The average yearly frequency of a rain event with a magnitude equal to or larger than event 2 is three, as mentioned in section 2.2. With this number we can calculate the total monetary damage due to floods caused by rain events equal to or bigger than event 2. This is equal to $3 \cdot 26,516 = 79,548$ GHS. Besides that it causes $3 \cdot 2700 = 8100$ vehicles to not arrive at their destination. A total number of $3 \cdot 770 = 2310$ people are affected by these floods yearly and risk getting diarrhoea due to E-coli in the water and $3 \cdot 0.15 = 0.45$ lives are lost because of the floods annually.

3.1.3. Event 3

Tangible damage

Figure 3.3 shows that a total of 47 stone houses and 34 self-made houses flood for rain event 3 for all the inundation depths combined. This causes a damage of 11,640 GHS and 2706 GHS. Besides the residential building there are 22 commercial buildings that flood, of which thirteen are shops and nine stalls. The flooded shops result in 1680 GHS of and the stalls in 2250 GHS of damage. Furthermore around forty percent of the agricultural land floods, resulting in 11,840 GHS of agricultural damage. The total monetary damage for event 3 altogether is 30,116 GHS.

Lake Road floods across the entire width for rain event 3, which causes no vehicles to be able to drive on the road for as long as the rain lasts. Rain event 3 lasts for six hours, resulting in $6 \cdot 900 = 5400$ vehicles not arriving at their destination.

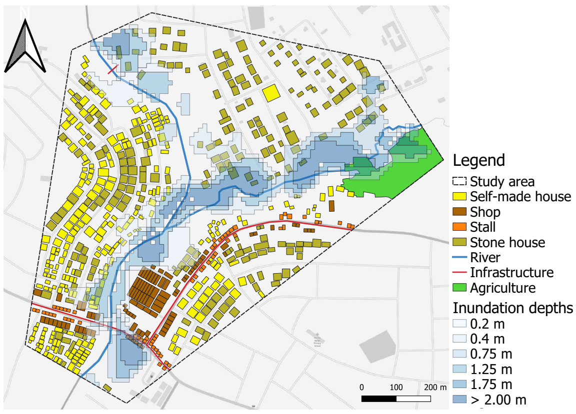


Figure 3.3: Flood map event 3

Intangible damage

In total 81 residential buildings flood during rain event 3, giving $81 \cdot 11 = 891$ people being affected by the flood. This means that there are 891 people exposed to E-coli bacteria in the water and risk getting diarrhoea. Furthermore $0.0002 \cdot 891 = 0.18$ lives are lost during rain event 3.

Risk analysis

Rain events with a magnitude equal to or larger than event 3 have an average yearly frequency of occurrence of $\frac{1}{3}$, as mentioned in section 2.2. This gives an estimated yearly monetary damaged caused by downpour similar to or larger than event 3 of $\frac{1}{3} \cdot 30,116 = 10,039$ GHS. Next to that $\frac{1}{3} \cdot 5400 = 1800$ vehicles will not arrive at their destination due to flooding, an average of $\frac{1}{3} \cdot 891 = 297$ people are affected and $\frac{1}{3} \cdot 0.18 = 0.06$ lives are lost annually.

3.1.4. Event 4

Tangible damage

There are both 44 stone houses and 44 self-made houses that flood during rain event 4. The flooded stone houses result in a total damage of 14,475 GHS and the self-made houses result in a total damage of 4178 GHS. Next to that there are fifteen shops that flood, resulting in 2730 GHS damage and thirteen stalls that flood, causing 2720 GHS of damage. Besides the buildings, 40 percent of the agricultural land floods, which result in 11,840 GHS of damage for the farmers. Combining the numbers gives a total monetary damage for event 4 of 35,943 GHS.

Furthermore, similar to events 1, 2 and 3, Lake Road floods across the entire width. This results in no vehicles being able to reach their destination for as long as the rain lasts, which is nine hours. So, in total there are $9 \cdot 900 = 8100$ vehicles that cannot reach their destination during rain event 4.

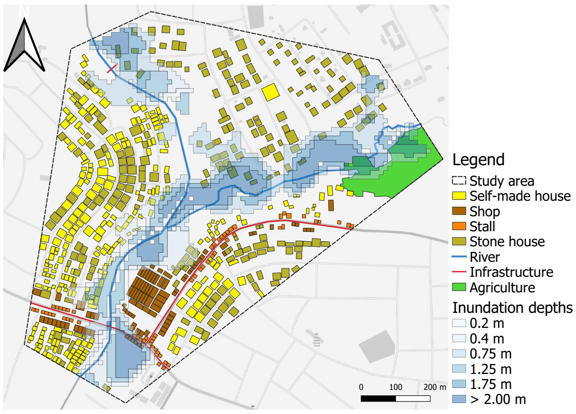


Figure 3.4: Flood map event 4

Intangible damage

As there are 88 residential buildings that flood during event 4, there are $88 \cdot 11 = 968$ affected by the flood. All of these affected people get in contact with the contaminated water and risk getting infected with E-coli bacteria, resulting in diarrhoea. From the number of people affected we can find that $0.0002 \cdot 968 = 0.19$ lives are lost in the flood.

Risk analysis

There is an average yearly frequency of occurrence for event 4 of $\frac{1}{3}$. This means that the average monetary damage due to downpour of equal to or larger magnitude than event 4 is $\frac{1}{3} \cdot 35,943 = 11,981$ GHS. Furthermore $\frac{1}{3} \cdot 8100 = 2700$ vehicles will not reach their destination annually and $\frac{1}{3} \cdot 968 = 322.7$ people are affected by the flood. Finally, on average $\frac{1}{3} \cdot 0.19 = 0.063$ lives are lost every year due to rain event with a peak precipitation equal to or larger than event 4.

3.1.5. Plastic blockage

The floods causing the most damage annually are caused by smaller downpours with a peak precipitation equal to or larger than event 1. This is because the smaller the taken peak precipitation, the more events are taken into account. For the quantification of the impact of plastic waste blockage to the flow we therefore compare the damage of the scenarios of event 1 without plastic blockage and with bridge 1 blocked for 67 percent.

Tangible damage

When the flow at bridge 1 is blocked for 67 percent by plastic waste, the number of stone houses increases from thirteen to seventeen and the damage increases to 5340 GHS. The number of self-made houses that flood does not change, nor does the damage to self-made houses. The number of shops that flood is equal with and without plastic blockage. The number of stalls that flood decreases with one, from seven to six, and the total damage decreases to 1160 GHS. The area of agricultural land that floods does not change and the damge will stay at 7400 GHS. The total monetary flood damage when bridge 1 is blocked equals 14,930 GHS.

Lake Road is still flooded across the entire width and therefore plastic blockage does not cause and increase in vehicles that cannot reach their destination. This number will still be 3600.

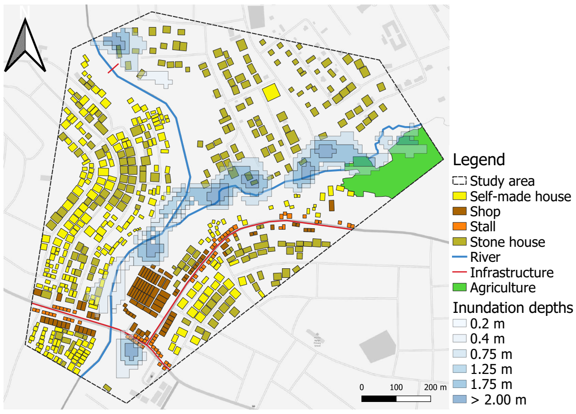


Figure 3.5: Flood map event 1 with bridge 2 blocked for 67 percent

Intangible damage

As the number of residential buildings flooded increases from 24 to 27, the number of people affected by the flood also grows. The number of people affected by the flood with bridge 1 blocked is $27 \cdot 11 = 297$, which is also the number of people exposed to the E-coli bacteria. An increase of the number of people affected causes the number of lives lost to grow to $0.0002 \cdot 297 = 0.06$.

Influence

The actual impact of the plastic blockage on the flow is calculated in percentage and absolute value compared to the scenario of event 1 without plastic. These numbers are given in table 3.1. We can see that the damage increases with 800 GHS and that 44 more people are affected by the flood.

	Percentage [%]	**Absolute value [GHS]**
Monetary damage	5.7	800
Traffic delay	0	0
Total people affected	17.4	44
Lives lost	20	0.1

Table 3.1: Percentage and absolute increase in damage due to plastic blockage of the flow

3.2. Discussion

3.2.1. Depth-damage curves

As mentioned in section 1.1.4 depth-damage curves overall have a correlation coefficient below 0.5, which means that the method itself has a considerable margin of error in translating inundation depth into monetary damage. More accurate methods of analysis require more data, however, depth-damage curve do give a first good impression of the magnitude of the damage.

3.2.2. Lack of data

With not all the needed data being directly available a lot of estimations had to be made, resulting in inaccuracies and uncertainties in the outcome of this research. Some of the estimations are more rough than others and some inaccuracies have a bigger impact on the outcome than others.

Residential and commercial buildings

Both residential and commercial buildings have been divided into two categories, but it is uncertain how accurate this this division is. Every building in the study area most likely has a different value and is built in a different manner. This automatically results in inaccuracies when buildings get clustered into categories without having individual assessment. Furthermore, assigning all the buildings in the study area to one of these categories was done with Google Maps as the main source. On Google Maps only the roofs of most buildings can be seen, which makes assigning a building to a specific category more prone to errors. Assigning buildings to the wrong category could result in large inaccuracies in the quantified damage.

Besides that the values taken for the damage to the buildings are based on rental prices for apartments from 2016. Even though the values have been checked and approved by Annor (2020), they are not the true damage values and it is uncertain how much they exactly approximate the true values.

Traffic

There is no data available on traffic counts or traffic densities on Lake Road, therefore this is estimated using an Indian design capacity, as mentioned in section 2.3.1. Even though the description of this design capacity meets the appearance of Lake Road on Google Maps, it is very uncertain whether this design capacity actually equals the traffic density on Lake Road.

Besides that the total amount of vehicles not arriving at their destination is based on the duration of the rain event. Even though it is likely that longer lasting rain hinders the traffic for a longer period of time, the duration of a rain event does not directly indicate for how long the water will stay on the road. Thus, there is also an uncertainty in the method of estimating how many cars cannot arrive at their destination due to floods

Frequencies

The average yearly frequency of the rain events and the floods they cause is only based on a period of three years. This could result in wrong interpretations of frequency and also could have rain events that happen less frequent to be missed out. Furthermore in the calculation of the risk the frequency is taken of rain events with an equal or higher peak precipitation than the modelled event. This means that for the risk calculation of event 1, events with a magnitude of event 2, 3 and 4 have also been taken into account.

People affected

In calculating the total number of people affected by a flood it has only been taken into account how many houses are flooded and how many people live in one house on average. This is a good estimation, but it is also prone to errors. The average number of people living in one house is the average for Atonsu as a whole and makes no distinction between houses. Some houses are much bigger than others and are home to more people. Besides, there could also be people affected in other ways than only by having their home flooded, which is not taken into account in the calculations.

Loss of life

There are no official records on historical floods in Kumasi. Therefore the mortality rate of floods is based on historical flood events in Ghana as a whole. There is a large margin of error in the mortality rate, as can be seen in the appendix in figure B.1. This margin could result in unacceptable differences between the actual and the estimated amount of lives lost, therefore the loss of life should not be taken as the most important outcome parameter of this research. It is on the other hand important to not forget that people die during the floods.

Waterborne diseases
The E-coli concentration in the river water that is used for calculation was measured in 2005 and for other pathogens the exact concentrations are unknown. This leaves big gaps in the estimation of water borne disease exposure due to floods in Kumasi. The calculations do show that, even after dilution by the rain water, the bacteria concentrations in the water are still way higher than acceptable. Therefore small inaccuracies in these numbers will not have a major influence, because the E-coli concentration will most likely still be way too high.

Infrastructure
Damage to infrastructure has not been taken into account for this research, but it could, as mentioned, happen that a bridge collapses because of a flood, which does certainly result in extra costs. It is however not known what the chance of collapsing is for a single bridge is and therefore it would be a too big uncertainty to take collapsing bridges into calculation. Furthermore the damge to the roads usually does not get repaired, as mentioned by Annor (2020). Howevet, this does not mean that nothing ever happens to the roads, it could be that once every couple of years the roads get repairing and that this repairing is more costly than it would have been if the roads never flood. This is however unknown and so not taken into account.

Agriculture
The flood damage to the agriculture is the most accurate of all. There is still a chance that the numbers do not exactly fit the agricultural land in the study area, because the number taken as financial loss per acre is an average. This difference is most probably small enough to be neglected.

4

Conclusions and recommendations

4.1. Conclusion

The research context of this bachelor thesis was to quantify flood damage associated with flood events caused by heavy rainfall and plastic blockage in Kumasi, Ghana. Before coming to the final conclusion and answering the thesis question of this research, the three sub questions are answered.

4.1.1. How can flood damage be quantified?

The most common division in quantifying flood damage is to make a distinction between tangible and intangible damage. Tangible damage covers all the damage that can be expressed in monetary values, while intangible damage is everything that cannot directly be expressed in monetary values, like loss of life, health related issues and damage to the environment.

There are different methods to quantify tangible damage, where depth-damage curves are the most simplified. Depth-damage curves only need the inundation depth to translate a flood into a monetary damage value. For some types of land use not the inundation depth, but only the inundated area matters, for instance with agriculture. In this case a curve can be constructed which shows the relation between the inundated area and the monetary damage. In countries like Ghana, where not a lot of data is available, using depth-damage curves to quantify tangible flood damage gives a good first impression of the magnitude of the flood damage. However, if it is desired to have a more accurate overview of the damage, more advanced multi-variable methods should be applied, like a regression tree or a Bayesian network (Wagenaar et al., 2017).

Quantification of intangible damage is more subjective compared to tangible damage, because one could not express a human life that is lost during a flood in money. Finding the number of people affected by a single flood could help finding possible fatalities and exposure to waterborne diseases. We estimated the number of people affected by a flood to be equal to the total number of people living in the flooded area. This can be calculated by multiplying the number of houses flooded by the average number of people living in one house. With data from historical flood events in the area a mortality rate can be calculated, which is the number of lives lost divided by the total number of people affected by the flood. This number could be used to estimate the expected number of fatalities in future floods. Furthermore, when bacteria concentrations in the river water are known and higher than tolerated, the number of people risking getting sick from these bacteria equals the total number of people affected.

4.1.2. What is the influence of plastic blockage on the quantitative flood damage?

Tjia (2020) showed that plastic blockage only increases the inundated area with one to three percent. The monetary damage due to the plastic blockage on the other hand, increases with an approximated 5.7 percent and the total number of people affected could increase with up to twenty percent. The increase of monetary damage mainly occurs because the inundation depths increase in certain parts of the study area due to the plastic blockages of the flow.

4.1.3. Who is affected by and would benefit from reduced flood damage?
Everyone living in the area is affected by the floods. If not directly because of their house, land or the shop they own being flooded, it could be because they cannot travel to work because of the roads being flooded. Reduction of flood damage would at first be beneficial for all the citizens of the area. Besides that also the municipality would benefit, as less repairing is needed when the flood damage lowers. Furthermore, if measures are taken by the municipality to reduce flood damage, this will have a positive effect on the image of the municipality, which is also beneficial.

4.1.4. General conclusion
What is the quantitative flood damage associated with flood events caused by heavy rainfall and plastic blockage in the neighbourhood of Atonsu in Kumasi, Ghana?

The quantitative flood damage exists of tangible and intangible damage. We have seen that for floods due to rain events with a regular appearance (event 1), the total monetary damage is 14,130 GHS. Furthermore there are 3,600 vehicles that cannot arrive at their destination and a total of 253 people are affected and risk getting diarrhoea from the contaminated water. It can be seen that the larger the rain event causing a flood, the greater the damage becomes. Furthermore plastic blockage results in an increase of monetary damage of 5.7 percent and up to 17.4 percent more people are affected by the flood when plastic blocks the flow of the water.

4.2. Recommendation
This research is a first step in the quantification of flood damage in Kumasi. It cannot cover the entire spectrum and is based on many assumptions. The results do show that the flood damage is quite significant and further research could improve the accuracy of the damage estimations. Collecting more accurate data will reduce the need of assumptions and therefore reduce inaccuracies. Furthermore, having long-term data collected would give the possibility to apply more accurate multi-variable methods compared to the depth-damage curves to quantify tangible damage.

Data of real events

Real data improves the accuracy of flood damage quantification. When it is known how many people are affected and how many lives are lost during flood events in Kumasi, a more accurate mortality rate can be calculated specifically for Atonsu, as the mortality rate used in this research is based on flood event in the entire country. Furthermore, if the damage to buildings is officially reported together with the inundation depth in the building, the accuracy of the depth-damage curves can be improved. Another thing that will improve when data of real events is collected is the frequency calculations of flood events, especially for a period of many years. When there is more data from a longer period of time, the probability becomes more reliable.

Fieldwork

Fieldwork in Atonsu will also improve the accuracy. The land use classification map used to quantify the flood damages is created using mainly Google Maps, which causes uncertainty in appointing buildings to a specific class. Being able to walk through the neighbourhood will take away a lot of estimation errors and improve the accuracy of the building classification. It could furthermore be seen whether the chosen building classes are appropriate or if the classes could better be shifted. Something else fieldwork would improve is the estimation of traffic densities on Lake Road. Sitting alongside the road for a day and counting the traffic will give a much more accurate estimation of the traffic density on Lake Road. In this traffic count a distinction between cars, vans and trucks could be made.

Methods

As depth-damage curves have a low accuracy in general, the method of quantifying tangible damage could be improved. To do so the previous mentioned data is needed in order to create a multi-variable which takes more parameters into consideration and could be tested using real data.

A

Calculations depth-damage curves

The depth-damage curves for residential and commercial buildings are constructed by first giving a schematic visualisation of the type of building with the different inundation depths. From this visualisation the damage factor for structural damage and furniture or inventory damage per flood depth can be derived. These damage factors together form a normalised depth-damage curve.

The normalised depth-damage curve is multiplied by the maximum damage value for the specific land use class and damage type. From this a quantified depth-damage curve is constructed. For residential and commercial buildings the two quantified depth-damage curves of the structural and furniture / inventory damage are added to form the final depth-damage curve.

A.1. Stone house

Figure A.1 shows a schematic representation of a stone house. The majority of the stone houses in the study area, especially in the flood prone parts, is single floored. This figure shows that stone houses are built on a foundation of an estimated 0.3 meters.

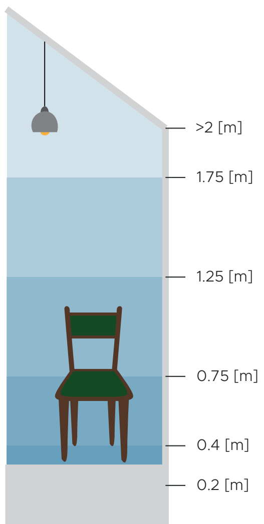


Figure A.1: Schematic visualisation of a stone house

Table A.1 shows the different flood depths with their corresponding damage factors and monetary values for structural damage to a stone house. This table also explains the origin of the damage factors. The damage factors combined give the normalised depth-damage curve of structural damage to a stone house, as shown in figure A.2 (a).

Furthermore the maximum damage value of structural damage to a stone house is taken to be equal to three months of rent of a double room apartment in the flood prone areas of Kumasi, which is around 450 GHS (Attakora-Amaniampong et al., 2016). The monetary damage values are calculated by multiplying this maximum damage value by the associated damage factor. The monetary values give the monetary depth-damage curve of structural damage to a stone house, as shown in figure A.3 (a).

Flood depth [m]	Damage factor	Monetary value [GHS]	Explanation
0.2	0	0	Due to the elevated floor no water enters the structure, so there will not be any structural damage and the damage factor is equal to zero.
0.4	0.2	90	Little water will enter the house, resulting in no real structural damage, but only cleaning costs. This is estimated to be one fifth of the maximum structural damage.
0.75	0.3	135	Rising water threatens to damage the electricity supply of the house, but will not damage the structure. The corresponding damage factor is estimated to be slightly higher, 0.3
1.25	0.5	225	A depth of 1.25 meters possibly results in broken windows and doors. This damage is estimated to be half of the maximum damage to a stone house.
1.75	0.9	405	There is a high risk of an in stable structure. Furthermore the entire house needs to be cleaned and is unlivable until cleaned, resulting in an almost maximum damage factor, 0.9.
>2.00	1	450	At this maximum flood depth the maximum damage factor is reached. At this point the house is unlivable and needs thorough cleaning and repair.

Table A.1: Damage factors and monetary values per flood depth for structural damage stone house

Table A.2 shows the different flood depths with their corresponding damage factors and monetary values for furniture damage to a stone house. This table also explains the origin of the damage factors. The damage factors combined give the normalised depth-damage curve of furniture damage to a stone house, as shown in figure A.2 (b).

Furthermore the maximum damage value of furniture damage to a stone house is taken to be equal to one month of rent of a double room apartment in the flood prone areas of Kumasi, which is around 150 GHS (Attakora-Amaniampong et al., 2016). The monetary damage values are calculated by multiplying this maximum damage value by the associated damage factor. The monetary values give the monetary depth-damage curve of furniture damage to a stone house, as shown in figure A.3 (b).

Flood depth [m]	Damage factor	Monetary value [GHS]	Explanation
0.2	0	0	Due to the elevated floor no water enters the structure, so there will not be any furniture damage and the damage factor is equal to zero.
0.4	0.3	45	The water that enters the house will affect all furniture on the floor, like carpets, but will not cause major damage to other furniture. Therefore the damage factor is equal to 0.3
0.75	0.6	90	At this flood depth chairs and sofas are damaged upto the seating and the fabric furniture will most likely need replacement, increasing the damage cost. Around sixty percent of the furniture is damaged or needs replacement, resulting in a damage factor of 0.6.
1.25	0.8	120	Most furniture is damaged with an inundation depth of 1.25 meters. Only lamps hanging from the ceiling and tall cupboard will stay untached, resulting in a damage factor of 0.8
1.75	1	150	None of the furniture will stay undamaged and will need to be either replaced or thoroughly cleaned with an inundation depth of 1.75 meters, so the damage factor is 1.
>2.00	1	150	At this maximum flood depth the maximum damage factor is reached.

Table A.2: Damage factors and monetary values per flood depth for furniture damage stone house

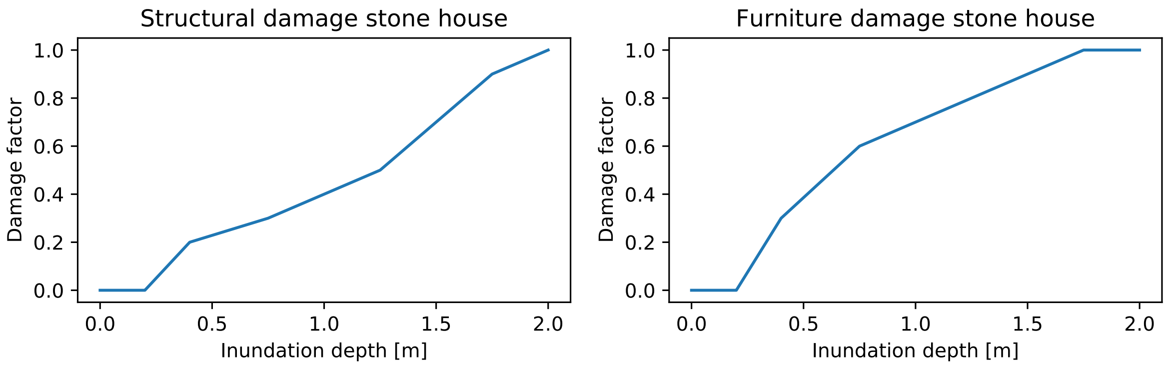


Figure A.2: Normalised depth-damage curves stone house (a) and furniture stone house (b)

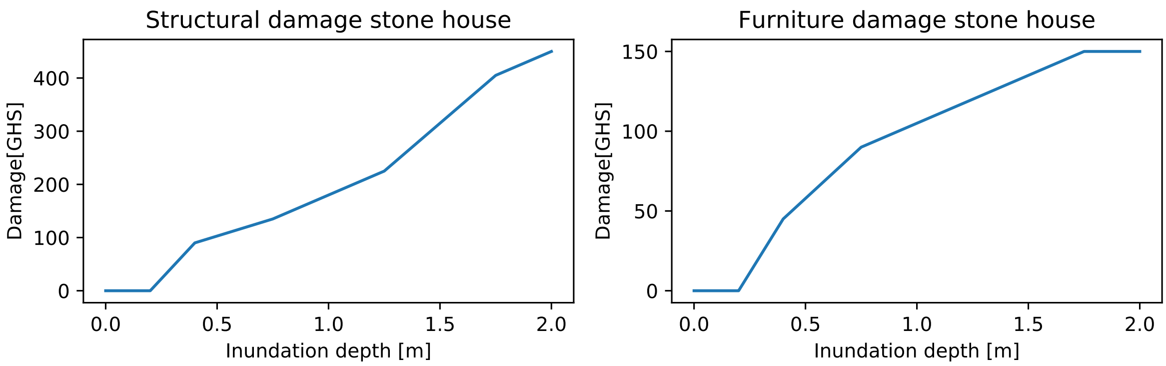


Figure A.3: Monetary depth-damage curves stone house (a) and furniture stone house (b)

By adding the monetary values for structural and furniture damage per flood depth the total monetary damage value per flood depth is calculated. The total monetary values per flood depth for stone houses can be found in table A.3. The final depth-damage curve used for the quantification of the total flood damage to stone houses is given in figure 2.5.

Flood depth [m]	**Structural damage [GHS]**	**Furniture damage [GHS]**	**Total damage [GHS]**
0.2	0	0	0
0.4	90	45	135
0.75	135	90	225
1.25	225	120	345
1.75	405	150	555
>2.00	450	150	600

Table A.3: Monetary values per flood depth for damage stone house

A.2. Self-made house

Figure A.4 shows a schematic representation of a self-made house. all the self-made houses in the study area are single floored, like shown in the figure. Furthermore the self-made houses are built directly on the ground, without a foundation.

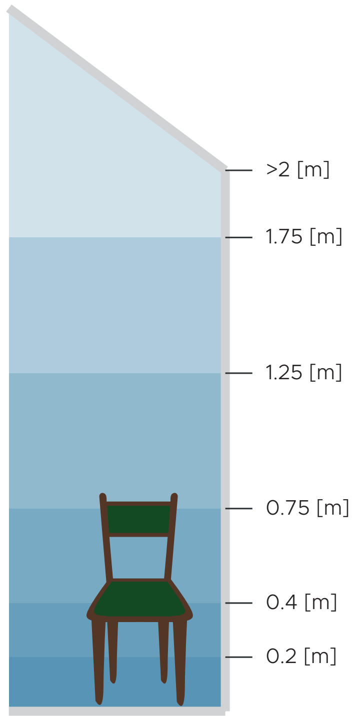


Figure A.4: Schematic visualisation of a self-made house

Table A.4 shows the different flood depths with their corresponding damage factors and monetary values for structural damage to a self-made house. This table also explains the origin of the damage factors. The damage factors combined give the normalised depth-damage curve of structural damage to a self-made house, as shown in figure A.5 (a).

Furthermore the maximum damage value of structural damage to a self-made house is taken to be equal to five months of rent of a single room apartment in the flood prone areas of Kumasi, which is around 100 GHS (Attakora-Amaniampong et al., 2016). The monetary damage values are calculated by multiplying this maximum damage value by the associated damage factor. The monetary values give the monetary depth-damage curve of structural damage to a self-made house, as shown in figure A.6 (a).

Flood depth [m]	Damage factor	Monetary value [GHS]	Explanation
0.2	0.2	20	Water right away enters the structure, but it will not cause a lot of damage, the costs will mainly be in cleaning. The damage factor therefore is estimated to be 0.2.
0.4	0.4	40	Rising water levels cause more damage. At this point the wooden walls of the house are getting wet with contaminated water, which could result in rotting. This makes the damage factor to be 0.4.
0.75	0.7	70	Chances rise of the structure collapsing, but most of the parts most likely could still be used when rebuilding the house. The costs do rise, due to the need of rebuilding, therefore the damage factor is 0.7.
1.25	0.8	80	Chance of collapsing rises, besides that there is an increasing chance of building materials falling apar or getting lost in the water. This makes the damage factor to increase to 0.8.
1.75	0.9	90	Again the chances of collapsing increase. The chance is again bigger that parts get lost or are unusable in rebuilding. So, the damage factor increases to 0.9.
>2.00	1	100	At this maximum flood depth the maximum damage factor is reached. At this point the house is very likely to have collapsed and is in need of major repair.

Table A.4: Damage factors and monetary values per flood depth for structural damage self-made house

Table A.5 shows the different flood depths with their corresponding damage factors and monetary values for furniture damage to a self-made house. This table also explains the origin of the damage factors. The damage factors combined give the normalised depth-damage curve of furniture damage to a self-made house, as shown in figure A.5 (b).

Furthermore the maximum damage value of furniture damage to a stone house is taken to be equal to three months of rent of a single room apartment in the flood prone areas of Kumasi, which is around 60 GHS (Attakora-Amaniampong et al., 2016). The monetary damage values are calculated by multiplying this maximum damage value by the associated damage factor. The monetary values give the monetary depth-damage curve of furniture damage to a self-made house, as shown in figure A.6 (b).

Flood depth [m]	Damage factor	Monetary value [GHS]	Explanation
0.2	0.3	18	All furniture on or close to the floor will get wet or damaged, especially carpets. Furthermore the bottom parts of all furniture standing on the ground needs to be cleaned. Tis results in a damage factor of 0.3.
0.4	0.6	36	Fabric furniture is unusable and soaked with contaminated water at this point, so it will be thrown away, increasing the damage factor to 0.6.
0.75	0.8	48	Most furniture is damaged at this flood depth. Only the higher placed furniture will remain untouched, which is not that much. So the damage factor is 0.8.
1.25	0.8	48	Most furniture is damaged at this flood depth. Only the lamps on the ceiling will remain untouched. This makes around 80 percent of the furniture to be damged or in need of replacement, giving a damage factor of 0.8.
1.75	1	60	All furniture is damaged and needs either replacement or to be cleaned very thoroughly. This gives the maximum damage value of 1.
>2.00	1	60	All furniture is damaged and needs either replacement or to be cleaned very thoroughly. This gives the maximum damage value of 1.

Table A.5: Damage factors and monetary values per flood depth for furniture damage self-made house

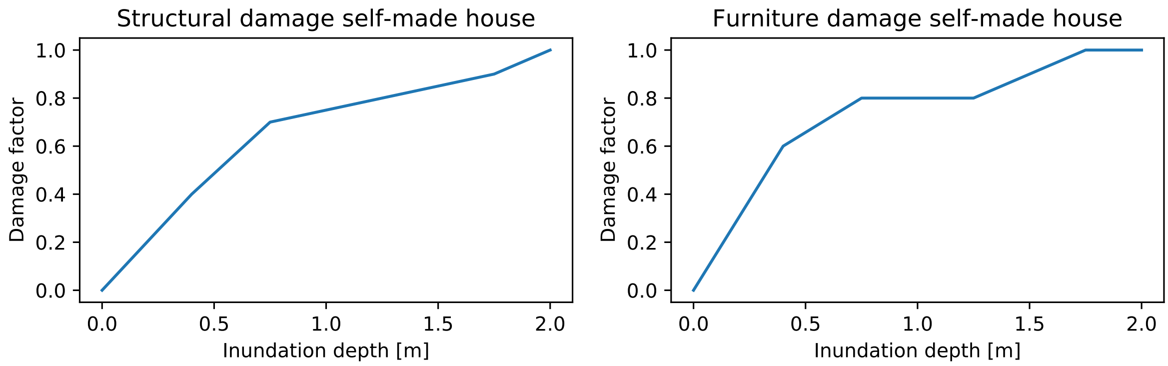


Figure A.5: Normalized depth-damage curves self-made house (a) and furniture self-made house (b)

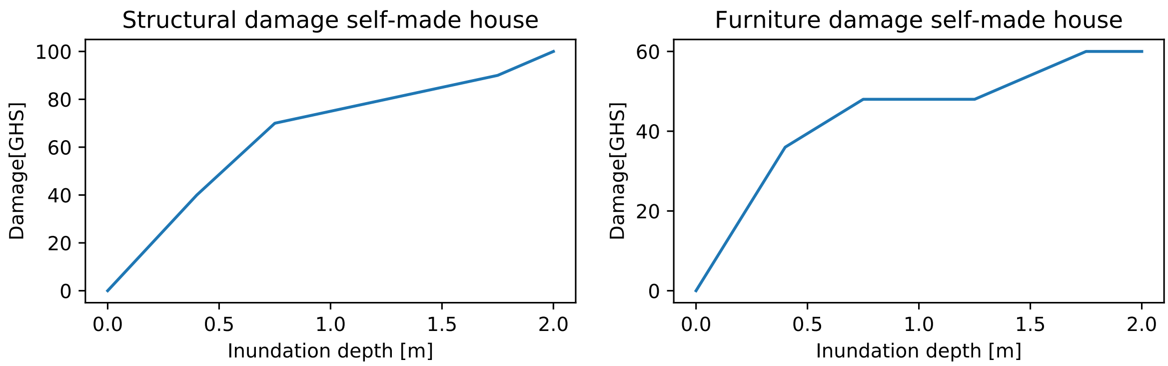


Figure A.6: Monetary depth-damage curves self-made house (a) and furniture self-made house (b)

By adding the monetary values for structural and furniture damage per flood depth the total monetary damage value per flood depth is calculated. The total monetary values per flood depth for self-made houses can be found in table A.6. The final depth-damage curve used for the quantification of the total flood damage to self-made houses is given in figure 2.6.

Flood depth [m]	**Structural damage [GHS]**	**Furniture damage [GHS]**	**Total damage [GHS]**
0.2	20	18	38
0.4	40	36	76
0.75	70	48	118
1.25	80	48	128
1.75	90	60	150
>2.00	100	60	160

Table A.6: Monetary values per flood depth for damage self-made house

A.3. Shop

Figure A.7 shows a schematic representation of a shop. The shops in the study area all have an elevated floor, either because of a thick concrete foundation or because the shop is build on wooden poles.

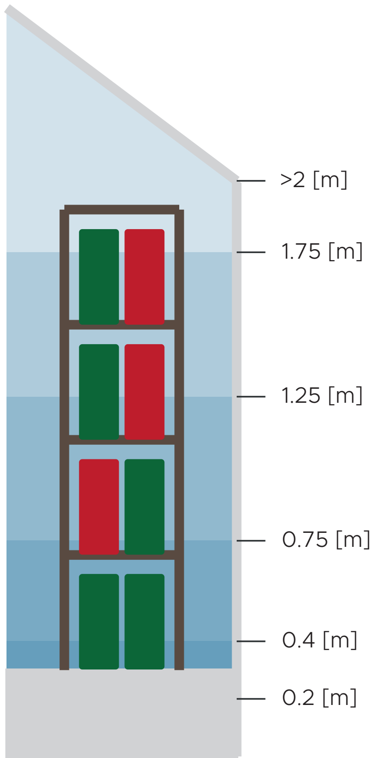


Figure A.7: Schematic visualisation of a shop

Table A.7 shows the different flood depths with their corresponding damage factors and monetary values for structural damage to a shop. This table also explains the origin of the damage factors. The damage factors combined give the normalised depth-damage curve of structural damage to a shop, as shown in figure A.8 (a).

Furthermore the maximum damage value of structural damage to a shop is taken to be equal to two months of rent of a double room apartment in the flood prone areas of Kumasi, which is around 300 GHS (Attakora-Amaniampong et al., 2016). The monetary damage values are calculated by multiplying this maximum damage value by the associated damage factor. The monetary values give the monetary depth-damage curve of structural damage to a shop, as shown in figure A.9 (a).

Flood depth [m]	Damage factor	Monetary value [GHS]	Explanation
0.2	0	0	Due to the elevated floor no water enters the structure, so there will be no structural damage and the damage factor is zero.
0.4	0.2	60	Little water will enter the shop, resulting in no significant structural damage, but mainly need for cleaning. This is estimated to be around one fifth of the maximum damage, so the damage factor is 0.2.
0.75	0.3	90	Rising water levels threaten to damage electricity supplies to the shop. It will however not yet cause ant major damage to the structure. The damage factor therefore is estimated to get slightly higer, up to 0.3.
1.25	0.5	150	There is a possibility of windows and doors to break because of the water. Besides that there is more cleaning costs. This in total is estimated to be half of the maximum damage and give a damage factor of 0.5.
1.75	0.9	270	There is a risk of instability of the structure. Furthermore the entire shop needs thorough cleaning, resulting in an almost maximum damage factor of 0.9.
>2.00	1	300	At this maximum flood depth the maximum damage factor is reached. The entire shop at this point is dirty and needs to be cleaned. Also there is a fair chance of parts of the shop to be broken and in need of replacement.

Table A.7: Damage factors and monetary values per flood depth for structural damage shop

Table A.8 shows the different flood depths with their corresponding damage factors and monetary values for inventory damage of a shop. This table also explains the origin of the damage factors. The damage factors combined give the normalised depth-damage curve of inventory damage of a shop, as shown in figure A.8 (b).

Furthermore the maximum damage value of inventory damage of a shop is taken to be equal to four months of rent of a double room apartment in the flood prone areas of Kumasi, which is around 600 GHS (Attakora-Amaniampong et al., 2016). The monetary damage values are calculated by multiplying this maximum damage value by the associated damage factor. The monetary values give the monetary depth-damage curve of inventory damage of a shop, as shown in figure A.9 (b).

Flood depth [m]	Damage factor	Monetary value [GHS]	Explanation
0.2	0	0	Due to the elevated floor no water enters the shop, so there will not be any inventory damage and the damage factor is equal to zero.
0.4	0.1	60	Most of the inventory is placed on shelves, only the inventory on the ground will be damaged, which is expected to only be around ten percent. This gives a damage factor of 0.1.
0.75	0.3	180	Inventory on the lower shelves gets damaged. It is taken that the inventory in a shop is equally divided from the ground up to the ceiling at 2.00 meters. Resulting in a slight increase of the damage factor to 0.3.
1.25	0.6	360	More than half of the inventory of most shops is located below this point, therefore just over half of the inventory gets damaged, resulting in a damage factor of 0.6.
1.75	0.8	480	Most of the inventory is damaged, only the inventory in the top shelves remains in tact. Around 80 percent of the inventory gets damaged, resulting in a damage factor of 0.8.
>2.00	1	600	All of the inventory, even on the highest shelves, gets damaged. This results in the maximum damage factor of 1.

Table A.8: Damage factors and monetary values per flood depth for inventory damage shop

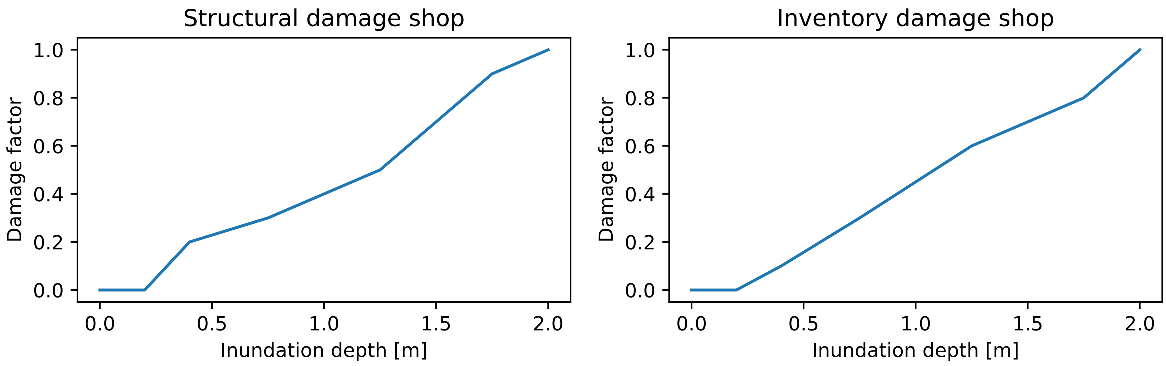


Figure A.8: Normalised depth-damage curves shop (a) and inventory shop (b)

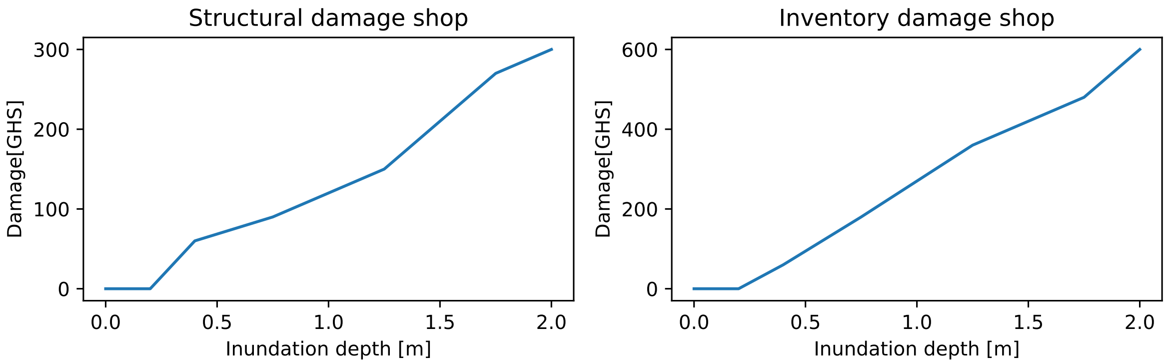


Figure A.9: Monetary depth-damage curves shop (a) and inventory shop (b)

By adding the monetary values for structural and inventory damage per flood depth the total monetary damage value per flood depth is calculated. The total monetary values per flood depth for shops can be found in table A.9. The final depth-damage curve used for the quantification of the total flood damage for shops is given in figure 2.7.

Flood depth [m]	Structural damage [GHS]	Inventory damage [GHS]	Total damage [GHS]
0.2	0	0	0
0.4	60	60	120
0.75	90	180	270
1.25	150	360	510
1.75	270	480	750
>2.00	300	600	900

Table A.9: Monetary values per flood depth for damage shop

A.4. Stall

Figure A.10 shows a schematic representation of a stall. all the stalls in the study area are primitive self-made stands, like shown in the figure 2.3b.

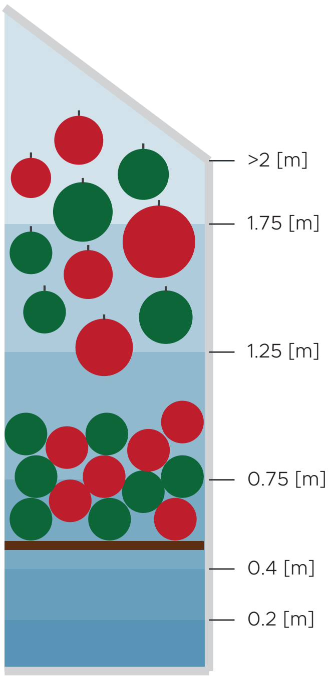


Figure A.10: Schematic visualisation of a stall

Table A.10 shows the different flood depths with their corresponding damage factors and monetary values for structural damage to a stall. This table also explains the origin of the damage factors. The damage factors combined give the normalised depth-damage curve of structural damage of a stall, as shown in figure A.11 (a).

Furthermore the maximum damage value of structural damage to a stall is taken to be equal to five months of rent of a single room apartment in the flood prone areas of Kumasi, which is around 100 GHS (Attakora-Amaniampong et al., 2016). The monetary damage values are calculated by multiplying this maximum damage value by the associated damage factor. The monetary values give the monetary depth-damage curve of structural damage to a stall, as shown in figure A.12 (a).

Flood depth [m]	Damage factor	Monetary value [GHS]	Explanation
0.2	0	0	The structure is elevated, so there will not be any real damage done to the structure with low flood depths. Therefore the damage factor is zero.
0.4	0.1	10	There is little cleaning cost, but no real damage to the structure. This results in an estimated ten percent of the maximum damage and has a damage factor of 0.1.
0.75	0.4	40	As the stalls are not very stable, there is a little chance of collapsing, but this is still low. The estimated damage factor that comes with this flood depth is, mainly due to the increase in cleaning costs, 0.4.
1.25	0.8	80	Collapsing is very likely with this flood depth. Furthermore the largest part of the structure will be either damaged or dirty, so repairing and cleaning is needed. This is almost as much as the maximum damage value and gives an estimated damage factor of 0.8.
1.75	0.9	90	With this flood depth the stall could be entirely washed away, and so large parts of the structure will be damaged or gone. The estimation is that around 90 percent of the maximum damage value is reached, giving a damage factor of 0.9.
>2.00	1	100	The highest flood depths will cause damage to the entire structure of a stall, thus giving a damage factor of 1.

Table A.10: Damage factors and monetary values per flood depth for structural damage stall

Table A.11 shows the different flood depths with their corresponding damage factors and monetary values for inventory damage of a stall. This table also explains the origin of the damage factors. The damage factors combined give the normalised depth-damage curve of inventory damage of a stall, as shown in figure A.11 (b).

Furthermore the maximum damage value of inventory damage of a stall is taken to be equal to ten months of rent of a single room apartment in the flood prone areas of Kumasi, which is around 200 GHS (Attakora-Amaniampong et al., 2016). The monetary damage values are calculated by multiplying this maximum damage value by the associated damage factor. The monetary values give the monetary depth-damage curve of inventory damage of a stall, as shown in figure A.12 (b).

Flood depth [m]	Damage factor	Monetary value [GHS]	Explanation
0.2	0	0	It is taken that all the inventory of a stall is placed above 0.5 meters. This results in low flood depths not resulting in any inventory damage and having a damage factor of zero.
0.4	0	0	It is taken that all the inventory of a stall is placed above 0.5 meters. This results in low flood depths not resulting in any inventory damage and having a damage factor of zero.
0.75	0.6	120	Half of the inventory is taken to be located on shelves at 0.5 meter hight. The rest of the inventory is taken to be equally divided between 0.5 and 2.00 meters. This results in 60 percent of the inventory being damages with a flood depth of 0.75 meters.
1.25	0.75	150	75 percent of the inventory gets damages with a flood depth of 1.25 meters, because of the equal distribution of the inventory between 0.5 and 2.00 meters.
1.75	0.9	180	With an inundation depth of 1.75 meters, around 90 percent of the inventory is damaged in a stall. This is estimated according to the destribution of the inventory.
>2.00	1	200	All the inventory is placed below 2.00 meters, therefore everything will be damaged with a flood depth of over 2.00 meters. This gives the maximum damage factor 1.

Table A.11: Damage factors and and monetary values per flood depth for inventory damage stall

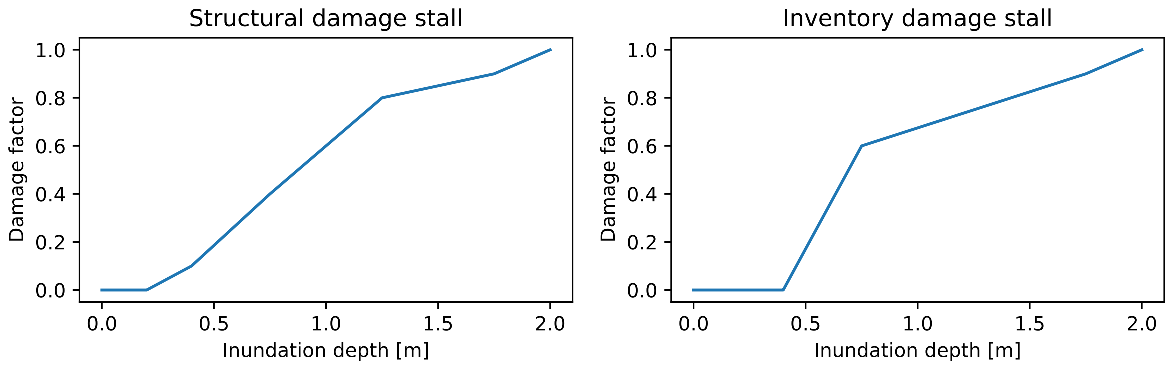


Figure A.11: Normalised depth-damage curves stall (a) and inventory stall (b)

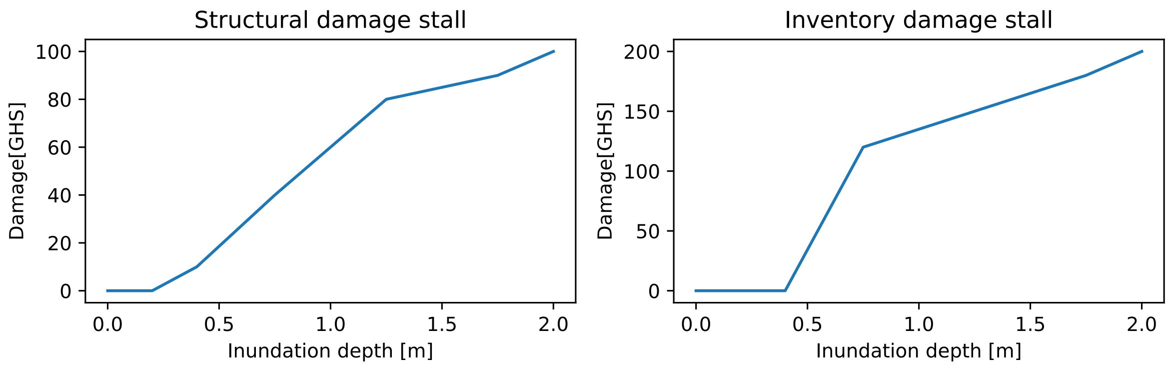


Figure A.12: Monetary depth-damage curves stall (a) and inventory stall (b)

By adding the monetary values for structural and inventory damage per flood depth the total monetary damage value per flood depth is calculated. The total monetary values per flood depth for stalls can be found in table A.12. The final depth-damage curve used for the quantification of the total flood damage to stalls is given in figure 2.8.

Flood depth [m]	**Structural damage [GHS]**	**Inventory damage [GHS]**	**Total damage [GHS]**
0.2	0	0	0
0.4	10	0	10
0.75	40	120	160
1.25	80	150	230
1.75	90	180	270
>2.00	100	200	300

Table A.12: Monetary values per flood depth for damage stall

B

Dataset historical flood events

This appendix contains the data used to find the mortality rate of floods in Ghana, which is used to estimate the number of lives lost per flood event in Atonsu, Kumasi. Table B.1 shows for each historical flood event in what year it took place, what the exact location was and what its origin was, as well as the total number of deaths and the total number of people affected.

The total number of people affected and the total number of deaths per flood event are plotted in figure B.1, through which the mortality line is fitted. This mortality has a slope of 0.0002, which is the mortality rate we use to calculate the loss of life for a single flood event in Atonsu.

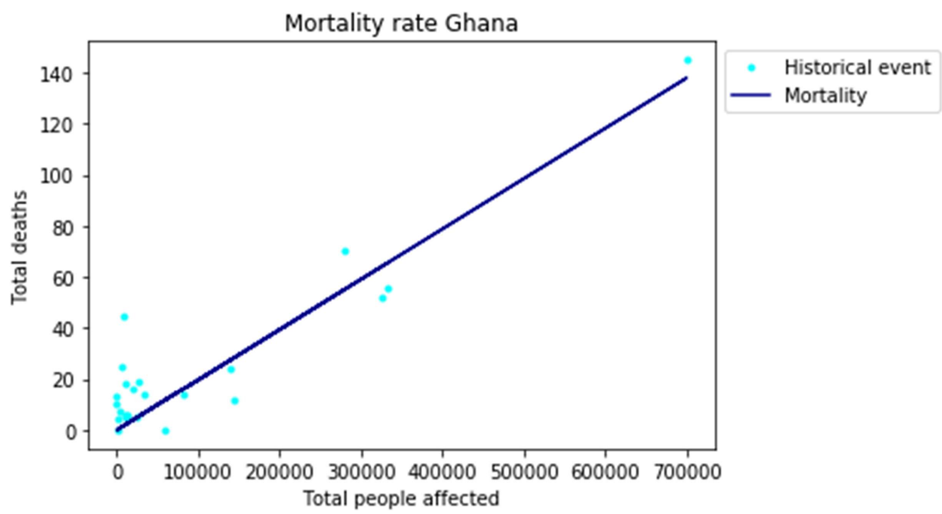


Figure B.1: Total number of people affected plotted vs. total deaths for historical flood events to calculate the mortality rate

Year	Disaster type	Country	Location	Origin	Total deaths	total affected	Source
1989	Flood	Ghana	Tamale		7	2800	EM-DAT (2020)
1995	Flood	Ghana	Accra		145	700000	EM-DAT (2020)
1999	Flood	Ghana	North	Heavy rain	70	280000	GLIDEnumber (2020)
1999	Flood	Ghana	North		52	324602	EM-DAT (2020)
2001	Flood	Ghana	Accra	Monsoonal rain	12	144025	EM-DAT (2020)
2002	Flood	Ghana	Accra		0	200	EM-DAT (2020)
2002	Flood	Ghana	Accra	Heavy rain	4	2000	EM-DAT (2020)
2007	Flood	Ghana	Upper East	Torrential rain	6	10000	EM-DAT (2020)
2007	Flood	Ghana	Builsa	Heavy rain	56	332600	EM-DAT (2020)
2008	Flood	Ghana	Mamprusi		0	58000	EM-DAT (2020)
2009	Flood	Ghana	Awoshie	Heavy rain	16	19755	EM-DAT (2020)
2009	Flood	Ghana	North	Heavy rain and dam release	24	139790	EM-DAT (2020)
2010	Flood	Ghana	Agina	Heavy rain	45	7500	EM-DAT (2020)
2010	Flood	Ghana	Brong Ahafo	Heavy rain and opening dike gates	18	9674	EM-DAT (2020)
2011	Flood	Ghana	East	Heavy rain	5	10000	GLIDEnumber (2020)
2011	Flood	Ghana	East	Torrential rain	6	12571	EM-DAT (2020)
2011	Flood	Ghana	Accra	Heavy rain	14	81473	EM-DAT (2020)
2013	Flood	Ghana	Gushiegu	Rainstorms	5	25000	EM-DAT (2020)
2015	Flood	Ghana	Accra	Torrential rain	25	5000	EM-DAT (2020)
2016	Flood	Ghana	Kwame	Torrential rain	10	0	EM-DAT (2020)
2019	Flood	Ghana	Accra and Kumasi	Heavy rain	14	34076	Ansah et al. (2020)
2019	Flood	Ghana	Accra	Heavy rain	13	0	EM-DAT (2020)
2019	Flood	Ghana	Bolgatanga	Heavy rain	19	26102	EM-DAT (2020)

Table B.1: Historical flood event in Ghana

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