WATER CONTAMINATION RISK DURING URBAN FLOODS

Using GIS to map and analyze risk at a local scale

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ABSTRACT

Water contamination during urban flood events can have a negative impact on human health and the environment. Prior flood studies lack investigation into how GIS can map and analyze this at a large scale (cadastral) level. This thesis focused on how GIS can help map and analyze water contamination risk in urban areas using LiDAR elevation data, at a large-scale (cadastral) level, and symbology and flood classification intervals specifically selected for contamination risk. This was done by first completing a literature review about past research and studies of similar scope. Based on the findings, a method to map and analyze water contamination risk during sea-based flood scenarios was tested in the Näringen district of Gävle, Sweden. This study area was investigated and flood contamination risk maps were produced for two different flood scenarios which illustrated which properties are vulnerable to flooding and at what depth, what their contamination risk is, and if they are hydrologically connected to the ocean. The findings from this investigation are that this method of examining water contamination risk could be useful to planning officials who are in charge of policies relating to land-use. These findings could help guide land-use or hazardous material storage regulations or restrictions. To further research in this topic, it is recommended that similar studies are performed that use a more detailed land-use map which has information on what type and quantity of possible contaminants are stored on individual properties. Furthermore, flood modeling should be employed in place of the flood mapping which was conducted in this thesis.

Keywords: GIS, urban flood mapping, contamination/pollution risk, LiDAR
PREFACE

This thesis was completed as the final requirement for the University of Gävle’s geomatic degree and as a partial requirement for a Thompson Rivers University geography degree.

I owe many thanks to my thesis supervisor, Nancy Joy Lim, who helped with the many stages of this thesis and with other coursework throughout the year. Also, I would like to thank Markku Pyykönen, Peter Fawcett, Anders Brandt, and Ross Nelson for their help with my thesis and coursework throughout my time at the University of Gävle.

Lastly, I appreciate all the support from my family and friends during my studies in both Canada and Sweden.

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1 INTRODUCTION

1.1 Background
Flooding occurs when water covers an area of land which does not usually contain any water. It is a natural phenomenon which occurs throughout the world and cannot be easily prevented. The European Exchange Circle on Flood Mapping (EXCIMAP, 2007) lists some common causes of flooding which include intense rainfall, snowmelt, storm surges, tsunamis, and high tides. Many coastal communities are vulnerable to flooding when one or more of these events occur (Webster et al., 2006). The consequences of flooding can include fatalities, human displacement, environmental impacts, and economic damage (European Commission, 2007).

When flooding occurs in urban locations, water contamination that can have a negative impact on human health, wildlife health, and the environment may occur from many different sources. The land-use type can be a good indicator of water contamination and pollution risk (Sood et al., 2012). EXCIMAP (2007) states that areas which pose a high contamination risk during flooding include fuel/gas stations, chemical industry warehouses, special dump sites for chemical or industrial waste, agricultural storage sites, waste water treatment plans, and more.

According to the World Meteorological Organization (WMO, 2008), if local planners and government officials have knowledge of flood characteristics and contamination sources, they can impose preventative measures, such as regulating or banning the storage and use of hazardous material in areas of high flood likelihood. This is important because flood water can drain back into rivers, oceans, and other sensitive areas without being filtered (as it typically is when passing through proper drainage systems) after urban flood events if storm water drainage systems have their volume and filtration capacities exceeded during flood events (Prodanoff & Mascarenhas, 2010).

Geographical information systems (GIS) have continued to improve and can be an effective tool in mapping, analyzing, and visualizing flood risk. Flood studies often deal with scenarios in which relatively small changes in water levels, often less than 1 m, can have severe impacts. Therefore, studies in this nature can obtain more accurate and usable results by using LiDAR data instead of traditional sources for elevation, due to its relatively fine horizontal resolution and low vertical uncertainty (Webster et al., 2006; Gesch, 2009; Cooper et al. 2012).

Flood vulnerability and risk maps are common and effective ways to visualize the potential effects of different inundation scenarios (Webster et al., 2006). These maps are useful to a wide range of groups that include local government, decision-makers, emergency personnel, and stakeholders (EXCIMAP, 2007; Stanchev et al., 2009).
1.2 Aims and objective of thesis

This study will attempt to show how GIS can help map and analyze locations which pose a water contamination risk during urban flooding. It will focus on the applicability, in a large scale, of detailed water contamination maps and how the risks can be visualized and used for planning. Additionally, the study will show how LiDAR data can be useful in such applications in an attempt to minimize uncertainty in the resulting maps. As a guide to this project, four specific research questions have been formulated:

1. How can GIS be used to map and analyze water contamination risk in urban flood events?
2. Compared with prior urban flood studies, how does using large scale (cadastral level) maps, LiDAR elevation data, and symbology and classification intervals selected specifically with water contamination risk in mind enhance the understanding of water contamination risk?
3. Compared with similar, often more general flood hazard mapping studies, what are the advantages and disadvantages of these visualization techniques?
4. What is the usefulness of this study in regards to urban planning in flood prone areas? Particularly, is large scale water contamination risk mapping desirable from a planning perspective? Why or why not?
2 REVIEW OF PREVIOUS RESEARCH

This section documents some past research that has been done concerning flood mapping with GIS, water contamination/pollution investigation with GIS, and using GIS as a visualization tool. It attempts to highlight what has already been done and what is missing in former studies. Note that some of the literature reviewed may seem somewhat unrelated to mapping flood contamination risk. However, they all exhibit at least one of the key aspects this study will investigate. A broad range of GIS, flood, and contamination related literature needed to be used for the review since there were few studies which utilized all the parameters this investigation attempted to incorporate.

2.1 Flood mapping with GIS

Flood mapping with GIS has been a widely investigated topic; this can be attributed to a variety of different reasons. For one, climate change and sea level rise (SLR) has become an increasingly important issue for many coastal communities. Many locations across the world can expect the severity and frequency of flooding to increase due to climate change. Therefore, land managers and planners have an increasing demand for information that will help them predict and manage areas that are at risk of inundation (McLean et al., 2001).

Webster et al. (2006) mapped SLR and storm surge scenarios in New Brunswick, Canada. They mapped floods caused from ocean levels that were between 0 to 4 m above mean sea level in 10 cm increments. Using LiDAR data as their elevation source, the results obtained were compared with past flood events of the area and were found to generally be accurate within 10 to 20 cm vertically. The published results are used to develop long-term adaption strategies for both natural and urban infrastructure. Cooper et al. (2012) performed a similar study using LiDAR data to map SLR scenarios in Maui, USA. Inundation maps were produced which predicted land loss due to inundation and financial loss estimates assuming no adaptive measures are taken. Webster et al. (2006) and Cooper et al. (2012) both project their flood maps onto high resolution orthophotos, which allow planners and officials to easily visualize major roads, municipal buildings, natural landscapes, etc. which will be inundated in the event that one of potential scenarios occurs.

Marfai and King (2008) perform more detailed investigations by incorporating a land-use map in their study in an attempt to develop a risk assessment for population, land-use, and monetary losses. Their study is located in Semarang city, Indonesia, and their land use map includes: agricultural and plantation area; built-up areas; fish ponds; bare land, beach and yards; sea, river and drainage systems; and, roads. This allows the study to quantify the total area that will be affected for the different land-uses, which in turn can estimate the economic cost (per ha) or the number of inhabitants that are at risk.

Lichter and Felsenstein (2012) conduct a similar investigation displaying how GIS can be used at a local level: “The paper [their study] shows how local planners can generate meaningful data at a high level of spatial resolution needed for rational decision making” (Lichter & Felsenstein, 2012). The authors mention that extreme flooding at a large scale has been overlooked and most studies are at a regional or national level. This is a useful finding for this current thesis, as it reinforces the need to further research in flood...
mapping at larger, more detailed scales. By using five different SLR increments, the authors investigate the land area affected, and give estimates of the costs in terms of capital stock at risk, and the population which is vulnerable to flood risk. However, this study does not use laser data for an elevation source; instead they use contour data to create their Digital Elevation Model (DEM). They do not mention which uncertainty data has, but they create flood intervals at 0.5 m and use these in their calculations. This may have been a source of inaccuracy which could have been improved by using LiDAR data for the elevation source.

Maantay and Maroko (2009) explore a Cadastral-Based Expert System (CEDS) to map urban flood risk in New York, USA. Wu et al. (2005) are quoted in this study saying that by performing population analysis using a large area (compared with cadastral based studies) and predetermined administrative boundaries (i.e. postal codes, census-tract boundaries, etc.), a false assumption is made that population distribution is even throughout that zone. Therefore, using GIS to map or analyze health studies, crime patterns, hazard/risk assessment, land-use planning, environmental impact studies, or other studies that require a fine resolution, or boundaries which differ from general ones, have the potential to be inaccurate. Maantay and Maroko (2009) mapped urban flood risk using 100-yr ocean levels; they found significant underestimation of population affected by flooding (37% - conventional areal weighting; 72% - centroid containment selection) using census data compared to their CEDS method.

2.2 Water contamination/pollution investigation with GIS
Sood et al. (2012) investigate how land-use affects storm water runoff quality in an attempt to discover which areas are main pollution sources. The land-use maps included common categories such as urban, industrial, commercial, residential, recreational, areas of heavy traffic, etc. They then took heavy metal, total suspended solids (TSS), and oil and grease samples from runoff areas which had different surrounding land-uses. The authors’ state: “It can be concluded from the study that pollutant concentrations vary considerably with land use pattern which indicates that pollutant distribution in the storm water is highly influenced by the surrounding land use type” (Sood et al., 2012). They found that industrial and commercial land-use posed the greatest contamination risk. The study utilized ArcGIS to map the land-use, plot the sampling sites, and spatially analyze the relationship between land-use and water pollution.

Diamantino et al. (2005) give an overview of several different methodologies used for assessing pollution vulnerability and risk for ground and surface water. One particularly interesting method discussed is called the Methodology of the ECOMAN Project. This method investigates surface water pollution by starting with a vulnerability map consisting of land cover, slope, soil, river network, and urban distribution. This map is then combined with a hazard map and pollution source map. The combination of these maps result in a final pollution risk map for surface water. The different methods for contamination mapping in this study use GIS for its classification abilities, overlay techniques, and creating vulnerability/risk maps that use different symbology to indicate risk.

2.3 Visualization with GIS
Using GIS to visualize or display spatial and numerical data can be a useful tool for many different scenarios. EXCIMAP (2007) has released a guidebook that discusses good practices for flood mapping in
Europe. Although they acknowledge that there is significant variance between different studies, they make several recommendations on different techniques to use for flood mapping visualization.

The guidebook suggests humans are socially conditioned to see the color blue as representing water, often flood extent or depth. However, when mapping flood risk of some type, they recommend red, yellow and green as an effective measure of the level of danger. If sub classification of a certain parameter is necessary, shading can be implemented (e.g. darker shades will represent increased severity). Line thickness, color, discontinuity, and definition can also help convey additional details when creating flood maps – often to represent observed vs. predicted floods or uncertainty of a certain parameter. It is also important to consider if the flood map being produced will need to be understood in a black and white print-scheme. Furthermore, it is recommended that the partially sighted and color blind be considered when producing flood maps (EXCIMAP, 2007).

2.4 Defining hazard, vulnerability, and risk
It is also important to define what is meant by flood hazard, flood vulnerability, and flood risk maps since the definitions can widely vary in different publications. Furthermore, different studies will include, exclude, or modify information shown on these flood maps to enhance the understanding of a specific project. It can become confusing when comparing similar studies as they may have significant differences in the way they label or classify hazard, vulnerability, and risk.

Hazard examples include earthquakes, floods, avalanches, fires, etc. Specifically relating to a flood hazard, common parameters that may be studied or included on flood hazard maps are water extent, velocity, depth, and duration.

Vulnerability can include potential death, destruction or damage to an area, or disruption to a specific item if a hazard occurs. This is a very general definition and different studies will usually focus on a particular vulnerability. Many flood hazard studies have focused on the vulnerability of loss of human life, contamination of water resources, financial implications, etc.

Risk is a combination of the overlap between a potential hazard and specific vulnerabilities. Theoretically, both hazard and vulnerability are needed for a risk to be present. A disaster cannot occur if a hazard occurs in an area with no vulnerability, or, if a vulnerable area is not affected by a hazard (Blaikie et al., 2004; Cançado et al., 2008).
3 METHODS

This section details the methods used to map flood contamination risk in the Näringen case study. Since a variety of former studies and investigations were reviewed, and few studies exist that use all of the key parameters selected for this thesis, there is not one single study method that has been specifically followed. Instead, methods and information were taken from a variety of studies. An attempt to document where a particular idea or method came from, and justify why it was used, is documented throughout this section.

3.1 Study area
The Näringen district of Gävle, Sweden will be used as a case study in this project. The land-use in the area is primarily industrial and commercial, which makes it a suitable location to test large-scale water contamination risk mapping since many of the contamination sources listed in EXCIMAP (2007) occur in areas of this nature (i.e. chemical industry warehouses, storage of hazardous material, etc.). Industrial and commercial land-use are also good indicators of pollution sources (Sood et al., 2012). The extent of the area that will be investigated is about 2.8 km² (Figure 1). Näringen is bordered by the Testebo River in the northeast, Baltic Sea in the east, the Gavle River in the south, and by Avaström in the west and northwest. During high river flows, ocean tides, and storm surges, the area is susceptible to flooding.

![Study area - Näringen district of Gävle](image)

Figure 1. Study area – Näringen district of Gävle

3.2 Data and materials
The data used in this study was collected from a combination of online public geo-databases and published reports. All data was retrieved as, or converted to the SWEREF99 Reference System.
The LiDAR elevation data was retrieved from the Swedish University of Agricultural Sciences’ Geodata Extraction Tool (GET, https://maps.slu.se/get/). This tool allows users to access and download a large range of geodata within Sweden. The data was delivered in .las file format and contained approximately 1.8 million points that were scanned during the collection of the New National Height Model elevation data. The National Land Survey of Sweden (Lantmäteriet) claims that the LiDAR data vertical accuracy is typically better than 0.1 m on flat, hard surfaces (Lantmäteriet, 2012). An orthophoto was also retrieved from the GET; the image has a production date of 2011 and has a resolution of 1 m.

The property boundaries for the Näringen area were obtained by creating a .tiff image from a screenshot of the cadastral parcels (fastighetsområden) in the Swedish National Geodata Portal (Geodataportalen, http://www.geodata.se/). This is another online tool which allows users to view and, in some cases, download geodata in Sweden. The land-use information for these properties was manually collected on May 16, 2013.

Two different 100-yr maximum high tide + 25 m/s wind storm surge water level scenarios were used to test the applicability of this investigation’s methods. These scenarios were obtained from a report by the Swedish Meteorological and Hydrological Institute (SMHI) and Swedish Geotechnical Institute (SGI) that investigated natural disaster vulnerability along Gävle’s coastline. The report (SGI & SHMI, 2012) was published in January 2012 and investigated extreme tides, storm surges, and sea level rise. Both scenarios are shown below in Table 1.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Water Elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present (2011) 100-yr maximum high tide + 25 m/s wind storm surge</td>
<td>1.47</td>
</tr>
<tr>
<td>2100 100-yr maximum high tide + 25 m/s wind storm surge</td>
<td>1.76</td>
</tr>
</tbody>
</table>

These scenarios were chosen since they were the most severe water levels cited in the report and they assured a possibility to map contamination risk during flooding scenarios. The value for the 2100 scenario is based on an assumed sea level rise of 1 m with considerations given to regional effects and land uplift. The full methodology used to obtain these values can be accessed in Stensen et al. (2010).

ESRI’s ArcMap 10.0 was the main GIS software used in this investigation. It was used to manage the LiDAR .las data used for the elevation source, produce hazard and vulnerability maps, and create the final contamination risk maps.

3.3 Creation of DEM

To create the Digital Elevation Model (DEM), the LiDAR data was first imported into ArcMap. Since the data was delivered in .las format, it needed to be converted to multi-points in order to analyze it with ArcMap. Only ground (class 2) and water (class 9) were used in the creation of the DEM; unclassified (class 1) were excluded because they consisted of buildings and vegetation point returns.
The next step in producing the DEM was to interpolate the multi-points, shown in Figure 2, since no data existed where building and some water areas were located. A 2 m grid size was used in order to assure that the raster cells would have adequate elevation data, which averages 1 m in spacing, to accurately interpolate from. As a quick check, a point to raster DEM conversion, using a 2 m cell size output, was performed for the area. The only areas which had no data were the building footprints and certain parts of the water, which meant a raster size of 2 m was appropriate. To fill-in the missing building footprints, a raster interpolation was completed using natural neighbor as the interpolation method. Natural neighbor, sometimes referred to as ‘area stealing interpolation,’ uses a subset of local samples to interpolate a missing point of data (query point). The interpolated query point always falls within the range of the local data samples which are being used in the interpolation. Therefore, this method will not infer any peaks or pits that do not already exist (ESRI, 2012). This method was chosen since it does not focus on overall trends and is heavily influenced by nearby cells.

3.4 Creation of land-use and land-use contamination vulnerability maps
The first step in creating the land-use map was to geo-reference an image, using ArcMap, of the Näringen property boundaries that was taken from the Geodataportalen (since a referenced image was not available for download to the public). The property boundary image included an underlying orthophoto, which allowed control points from the orthophoto in this image to be matched to the corresponding locations on the geo-referenced orthophoto obtained from the GET. Next, using ArcMap, the digitization of the property boundaries were completed for the Näringen area on the east side of the railway tracks. The
properties on the western side were not included as they have no risk of flooding due to their elevation being above the two flood scenarios used in this study. Also, several properties in the top, northwest corner of the official Näringen boundary were left out of the study area as they, apart from one small underpass location, are not vulnerable to flooding.

Four properties which border the Näringen Sea had their official property boundaries extend into the sea; these were edited so that their boundaries ended on land. This was done in order to not have these properties be classified as vulnerable to flooding unless their usual dry areas became inundated. The original and edited property boundaries are shown in Figure 3.

![Figure 3. Original (left) and edited (right) property boundaries used for land-use map](Orthophoto Copyright © Lantmäteriet, i2014/00655)

The land-use information was collected manually. The categories included were industrial (I), commercial locations that were likely to store large amounts of contaminants – commercial hazardous (CH), commercial locations unlikely to store large amount of contaminants (C), government institutions (Gv), open areas (O), and green space (G). Their classes are rather broad but since manual surveying was the collection method, it needed to be simple enough to be achievable. For reference, CH properties consist of paint stores, hardware stores, car washes, etc.; C properties consist of restaurants, grocery stores, and other properties which were not expected to contain large amounts of contaminants or pollutants.

A final land-use contamination vulnerability map was constructed which rated each property lot as high, medium, and low in terms of contamination vulnerability during flooding. I and CH were ranked as high, C and Gv as medium, and O and G as low. This was based on the findings of Sood et al. (2012) that industrial and commercial properties were most likely to contain major pollutants or contaminants.

### 3.5 Creation of flood hazard maps

Flood hazard maps which include water extent and water depth data were produced for the 2011 (herein referred to as present) and 2100 100-yr maximum high tide + 25 m/s wind storm surge levels. To produce the hazard maps, the DEM was subtracted from both the present and 2100 scenarios (shown in Table 1) to produce new raster layers that display flood depths. A reclassification was performed to create a final
flood hazard map which includes flood extent and flood depth information. The reclassification performed
is presented in Table 2. The reasoning behind the recoded flood depths was to use intervals that were
chosen specifically with contamination risk during flooding in mind. These depth intervals were proposed
after reading a report by The Royal Institute of British Architects (RIBA, 2009) and their statements that
flood water can carry urban debris starting at approximately 0.25 m, and at depths of over 1 m, water can
start to move or carry objects the size of cars. Therefore, the idea behind the three depth classes is that:
1) flood depths less than 0.25 m are susceptible to contamination via pollutants that have been spilt or are
stored directly on or in the ground; 2) flood levels between 0.25 to 1 m will be susceptible to contamination
via smaller objects, e.g. oil drums that may overturn or bags or boxes of pollutants that are stored near
ground level; and, 3) water levels over 1 m will be susceptible to overturning larger sources of pollutants,
e.g. cars, machinery, or large storage tanks that may contain hazardous material.

Table 2. Flood depth recoding used in the creation of the flood hazard maps

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Recoded to</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0</td>
<td>No Data</td>
</tr>
<tr>
<td>0 &lt; 0.25</td>
<td>1</td>
</tr>
<tr>
<td>0.25 - 1</td>
<td>2</td>
</tr>
<tr>
<td>&gt; 1</td>
<td>3</td>
</tr>
</tbody>
</table>

3.6 Producing contamination risk maps
The final contamination risk maps were completed by combining the final land-use contamination
vulnerability map with the flood hazard maps. Using ArcMap’s overlay tools, properties were included in
the contamination risk map if the flood scenario extent intersected their boundaries. These properties
were then assigned a value which indicated the depth of flood that would occur on their lot. This
calculation was set to return the highest value present if more than one flood depth occurred on the same
parcel. With both land-use and depth known for each flooded parcel, the last step was to assign the
individual properties a value between one and nine. The assignment rules used are shown in Table 3.

Table 3. Final contamination risk map coding used in the creation of the contamination risk maps

<table>
<thead>
<tr>
<th>Land-use</th>
<th>Flood Depth: &lt;0.25 m</th>
<th>Flood Depth: 0.25 m-1 m</th>
<th>Flood Depth: &gt;1 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Contamination Vulnerability</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Medium Contamination Vulnerability</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>High Contamination Vulnerability</td>
<td>7</td>
<td>8</td>
<td>9</td>
</tr>
</tbody>
</table>
Using some of the findings on GIS visualization in the literature review section, the individual properties were colored based on human perceptions to risk. The low risk land-use areas that were vulnerable to flooding were colored green, medium risk yellow, and high risk red. The depth of the flood was represented by different shades: the lightest shade represented the least severe flood depth, while the darkest shade represented the most severe flood depth interval.

The final step in the contamination risk maps was to classify which flooded parcels were hydrologically connected (HC) and hydrologically disconnected (HD) to the ocean. This was done by first exporting the HC polygon from the vector file into its own layer. This layer was then overlain with the flood contamination risk map and all properties at risk to flooding were coded as HC or HD. All HD properties were then exported into their own layer. These were symbolized with a 10% simple hatch cover and overlain onto the final contamination risk map.
4 RESULTS

This section displays the results from the methods section. The final flood contamination risk map for the present and 2100 100-yr maximum high tide + storm surge scenarios are displayed, as well as other important criteria that were used to derive them.

4.1 Land-use and land-use contamination vulnerability maps
The manually surveyed land-use map is shown below in Figure 4. The majority of the properties were classified as industrial, followed by commercial (hazardous), and then commercial; the remainders were roughly split between government, open area, and green space.

![Land-use Classification](image)

Figure 4. Land-use classification map that was manually collected on May 16, 2013

The land-use contamination vulnerability map in Figure 5 is a further aggregated land-use map which categorizes the contamination vulnerability in three different categories – low, medium, and high. As evident, much of the area consists of land-use that has been designated as a high vulnerability for water contamination if flooding occurs. This is followed by medium vulnerability properties. Low vulnerability
properties account for only a small portion of the study area. Table 4 displays the total area which all three categories account for.

**Figure 5.** Land-use contamination vulnerability map derived from the land-use classification map. The original six land-use classes were separated into three different vulnerability levels – low, medium, and high.

**Table 4.** Total area for the different contamination vulnerability classes

<table>
<thead>
<tr>
<th>Land-use</th>
<th>Area (square meters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Contamination Vulnerability</td>
<td>50,883</td>
</tr>
<tr>
<td>Medium Contamination Vulnerability</td>
<td>195,043</td>
</tr>
<tr>
<td>High Contamination Vulnerability</td>
<td>588,832</td>
</tr>
</tbody>
</table>
4.2 Flood hazard maps

Figure 6 represents the flood hazard map, which shows flood depth and extent, for the study area under the present 100-yr maximum high tide and storm surge scenario. This scenario resulted mainly in roadways and the adjacent property edges flooding. There are a few locations which have the majority of their properties flooded in the middle and eastern edge of Näringen. The flood depth >1 m evident in the southwest corner of Figure 6 is a low-lying underpass.
Figure 7 represents the flood hazard map for the study area under the 2100 100-yr maximum high tide and storm surge scenario. Compared to the present hazard map, this event encountered an increase in total flooded area of many vulnerable properties. The possible flood locations in this scenario also have a greater connectivity to the sea compared with the present scenario.
4.3 Contamination risk maps

Figure 8 displays the HC flood extent that was used to classify the different at risk properties as HC or HD for both the present and 2100 final contamination risk maps. In Figure 8, the present scenario was shaded light blue because it represents the least severe flood (depth wise) out of the two flood scenarios. The dark blue water represents the more severe (depth wise) 2100 flood scenario. The present flood layer was overlain on top of the 2100 layer in an attempt to showcase the additional area which the 2100 flood scenario occupies.
Figure 9 shows the final contamination risk map under the present 100-yr maximum high tide and storm surge scenario. Although the land-use contamination vulnerability and flood hazard maps were combined to make nine different classes, only seven exist for this scenario since no low risk properties had flood depths greater than 1 m and no medium risk properties had a flood depth exceeding 1 m. In total, 24 of the 33 properties which are a contamination risk in this scenario are hydrologically disconnected from the sea.
Figure 10 illustrates the final contamination risk map under the 2100 100-yr maximum high tide and storm surge scenario. There are eight contamination risk classes in this map since there are no medium risk properties with a flood depth that exceeds 1 m. More of the at-risk properties are hydrologically connected to the ocean under this scenario; only nine of the 49 at-risk properties are hydrologically disconnected.

Figure 10. Contamination risk map for 2100 100-yr maximum high tide + storm surge scenario
5 DISCUSSION

This section discusses the results and findings of the Näringen case study and how they can be analyzed in order to gain insight to the aims and research questions that were formulated for this investigation. As previously stated, the research questions this investigation attempted to address were:

1. How can GIS be used to map and analyze water contamination risk in urban flood events?
2. Compared with prior urban flood studies, how does using large scale (cadastral level) maps, LiDAR elevation data, and symbology and classification intervals selected specifically with water contamination risk in mind enhance the understanding of water contamination risk?
3. Compared with similar, often more general flood hazard mapping studies, what are the advantages and disadvantages of these visualization techniques?
4. What is the usefulness of this study in regards to urban planning in flood prone areas? Particularly, is large scale water contamination risk mapping desirable from a planning perspective? Why or why not?

Limitations this investigation and case study faced are also discussed. Furthermore, recommendations into further research in this topic are suggested.

5.1 Research questions findings

ESRI’s ArcMap software was used in this investigation in order to map and analyze water contamination risk during flood events by using a large scale (cadastral level), LiDAR elevation data, and symbology and classification intervals designed to specifically relate to water contamination risk. By using LiDAR elevation that is accurate within 10 cm, combined with a large scale map which investigates single properties, detailed DEMs, flood results, and at-risk properties were obtained that, theoretically, have relatively low uncertainty. By combining these parameters with flood depth intervals and visualization techniques that were specifically chosen to rank contamination risk, specific maps which illustrate water contamination risk are obtained.

By completing this study at a large scale (cadastral level), detailed hazard, vulnerability, and risk maps were able to be produced. In many similar studies, a smaller scale (larger area) is often used and flood or contamination information may be available only for entire neighborhoods, cities, or regions; this makes trying to determine if individual properties are at-risk unattainable. Since this study worked at a very large scale (cadastral level), a source of elevation data with a relatively low uncertainty was needed. Therefore, by using LiDAR data, this study was able to use elevation data with an accuracy which is usually better than 0.1 m on flat, hard surfaces (Lantmäteriet, 2012). Finally, this study employed symbology and classification intervals selected specifically with water contamination risk in mind. The symbology used was quite common in similar studies, however, the classification intervals were more unique. By using intervals that were specifically selected for contamination risk, an attempt to improve the prediction of the level of contamination that will occur in certain floods was completed. Some similar studies, including Webster et al. (2006), use even intervals such as 100 cm to classify a floods depth. However, according to RIBA (2009), flood water can carry urban debris starting at approximately 25 cm. Therefore, in some other studies, a
A standard interval of 0 to 100 cm and 100 to 200 cm would classify 20 or 40 cm as having the same amount of contamination risk. Yet, in this study, a flood depth below 25 cm would be classified as the lowest contamination risk, whereas a flood depth of 40 cm would be classified as a greater contamination risk.

A study similar to this investigation has many advantages. As previously discussed, using a large scale – cadastral level, LiDAR elevation data, and symbology and classification intervals selected specifically with water contamination risk in mind allows a theoretically more detailed (at a large scale) study, more accurate predictions due to an elevation data source with relatively low uncertainty, and a better study for predicting contamination implications during flooding due to setting up symbology and water intervals specifically selected for this task. However, the methods carried out in this investigation also have disadvantages. The study is quite time-consuming as specific data needs to be collected, and the analysis has to be done at such a large scale. The process would turn into a large amount of work if it was attempted in a large metropolitan coastal city where thousands of property boundaries exist. Näringen had fewer than 100 properties to analyze. Furthermore, although a highly detailed result is obtained for flood contamination risk, the usefulness of the investigation stops there. Unlike the Marfai and King (2008)’s study, this investigation cannot apply its results to economic damage or population affected. By performing detailed studies that only investigate one topic, the applicability of using the study for other issues is lost. This study also has the potential to have a greater cost compared to more general studies. LiDAR elevation may cost more money and be more time consuming than using contour data. Furthermore, since this study is only useful for contamination risk during flood events, Näringen would have to complete additional studies for economic loss or population vulnerability, whereas, Marfai and King (2008)’s study supplies all of these components – although at a more general and less detailed level.

With a land-use contamination risk classification system that contains more detailed information on contamination sources and flood data that is modeled rather than mapped, the methods carried out in the Näringen case would be useful to planners and officials. It is likely that such officials would have access to, or be able to attain, more detailed information on what type and quantity of pollutants are stored on specific properties. By having access to this data and modeling flood scenarios, the method employed in this investigation would allow city planners and officials to work with properties of high risk on decreasing or eliminating potentially undesirable contamination scenarios from occurring during flooding. This may be through upgrading their infrastructure to protect hazardous materials from flooding, or to regulate what can be stored on site. Many other studies utilize elevation data which is not LiDAR derived, do not complete the study at a cadastral level, and do not choose such a specific topic to investigate (i.e. more general aims). If a similar study was completed in Näringen, it would be difficult for planners and officials to accurately estimate contamination risk and impose any regulatory guidelines on the area due to the uncertainty and generalness of the study. It is likely that a study which employs similar methods to this thesis is more desirable from a planning perspective for water contamination risk than a more general study would be. However, depending on resources and budgets, studies similar to this may or may not always be feasible. Ultimately, city officials and planners may only be interested in having a similar investigation completed for areas that are known to have many severe at-risk properties (heavy industrial, refineries, etc.) for water contamination risk and/or if they have a budget which allows for similar work to be performed.
5.2 Limitations
This study did not employ any flood modeling, just flood mapping. This was done by simply applying a constant water elevation to all the DEM cells which fall below a certain scenarios value. As Webster et al. (2006) point out, this method fails to account for any hydraulic effects, time lags, or flood expansion or dampening. Another hydrologic factor that was not considered was storm water catchment systems and their locations or capacity. Because of this, hydrologically disconnected cells were left in this study as storm water catchments have the ability to transport water into locations that will not be susceptible to flooding via surface flow.

Land-use data was another limitation this study encountered. Since the official cadastral data is classified and takes time to access, manual surveying of the land-use was performed instead. This is not an ideal system as it is susceptible to certain types of error and limitations. For one, only so much information can be gathered about a property without having access into the building or access to official data. One example of this problem would be classifying a building that is only vaguely labeled *XX-Insulation*. It can be hard to identify if it is a commercial building that only stocks finished product that poses no contamination vulnerability, or if manufacturing takes place on-site and should be classified as industrial. It would also be beneficial to have the history of property use. A specific property may be classified as green space and therefore have a low contamination vulnerability assigned to it. However, if the property was historically used for industrial purposes, the soil on site could still contain high levels of contaminants which warrant a higher vulnerability assignment. Furthermore, the low-high contamination vulnerability classification system used in this study is quite basic. Local municipalities are more likely to have access to information about type and quantity of hazardous material that is stored on land parcels. This would allow a more complex and accurate contamination vulnerability classification system to be derived.

At times the property boundaries had mixed use and had to be classified into their more hazardous value. For example, industrial and non-hazardous commercial was classified as industrial. Several properties were inaccessible by foot and had to be classified by Google Earth and satellite photos, however, these were almost certainly industrial areas and misclassification was not a large concern with them.

Finally, the overlaying technique that was used to derive if a property would become inundated under a flood scenario is not flawless. If you look at flood hazard maps for both the present and 2100 flood scenarios in figure 6 and figure 7, it is evident that the inundated areas are often along the roadways and their immediate surrounding area. This is especially noticeable in the present scenario displayed in figure 6. Therefore, if a property only has its driveway or outside edge flooded, it will receive the same classification that a completely inundated property will receive.

5.3 Recommendations
In the future, similar studies could be performed with a more detailed contamination vulnerability classification system for the properties. The methodology for this will depend on which data is accessible and where the investigation takes place, since different contamination risk will be present in agriculturally intensive regions versus industrial intensive locations. Furthermore, the low vertical uncertainty of this study, due to the LiDAR elevation data, allowed a theoretically fairly accurate DEM to be constructed. However, this DEM is then overlain by flood extent and depths that were not hydraulically modeled and
almost certainly contain some significant error due to their simplicity. If a more detailed contamination-risk classification system was used with modeled flood data, a more detailed and accurate investigation could conceivably be completed.
6 CONCLUSIONS

This thesis investigated the applicability of using GIS to map and analyze contamination risk during flooding by utilizing LiDAR elevation data, a large scale (cadastral) level of study, and flood depth intervals and symbology specifically selected with contamination risk in mind. After a literature review was completed to derive what prior studies lacked, and to strengthen the understanding of how GIS can be of assistance in this scope, a case study in Näringen, Gävle was performed. Using the parameters of interest, flood water contamination risk maps were completed for two different scenarios in the study area (i.e. the 2011 and 2100’s 100-yr maximum high tide + storm surge). The results indicated that although the methods applied here can be time consuming, they should be useful to aid urban planners and city officials to better understand what contamination risks are present in flood prone areas. This knowledge can aid in creating restrictions or guidelines on land-use or hazardous material storage in flood prone locations and/or formulate appropriate response plans for flooding scenarios. However, to increase the knowledge-base in this topic, similar investigations should be performed which utilize more specialized land-use contamination risk maps and conduct flood modeling, rather than the simple flood mapping this study employed.
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