Modelling flood streams for urban planning in Trondheim, Norway

Project
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Acknowledgement

I would like to thank my colleagues from the Division on Surface and Sewage Water for the very good cooperation on this project, especially Birgitte Johannessen and Olav Nilsen.

The workshops with other municipalities in Oslo, supported by "Cities of the Future", where very helpful to discuss the method and experiences. Thanks a lot to all the people who were involved!

Many thanks also to Christoph Traun, my supervisor at UniGIS Salzburg, who gave helpful advice for the writing of the report.

And last not least a warm thank you to my family and friends for their encouragement and understanding.

Foreword

"Smart people learn from other`s mistakes, the average learns from their own mistakes, the stupid not even that." (Anonymous)

According to this dictum, I hope that I belong to the „average". And I hope, that you, dear reader, will become a bit smarter by this lecture.

Title Picture: Flooding in February 1999 of the "Fredlybekken", rightly shown in the analysis as a combination of a sink area and flood streams.

Abstract

The main objective of this project was to determine flood streams that accumulate after heavy rain falls for the community of Trondheim, Norway. The project was carried out during the years 2011 and 2013.

The analysis is based on height models that are generated from laserdata and 3D vector data for the whole township area. Tools from ArcGIS Spatial analyst and 3D analyst were used for the preparation of the data and the hydrological analysis. The major challenge showed to be the construction of hydrological correct height models.

The analysis was carried out for a situation in winter when the ground is frozen and ice and snow are blocking most of the ducts for the surface water. Two scenarios were modelled: A complete blocking of all ducts by ice and snow and a situation where major ducts are still functioning. The main result consists of line features indicating the location of flood streams and their relative size measured as the extent of the water catchment area draining into the respective feature object.

A one-day field assessment indicated an overall satisfying accuracy. It also revealed disadvantages of the used tools. Both the restrictions and advantages of the method are presented. The report finishes with an overall conclusion and a discussion of possibilities for improvement and options for the application of the results.

Figure 1: View from the south on the town centre of Trondheim. (TM 2008)

Figure 2: View from the northeast on the main lake "Jonsvatnet", the source of drinking water for Trondheim. (TM, N.D.)

Content

1   Introduction

1.1   Background

The National Planning and Building Act in Norway (MD 2008) states that local municipalities are responsible for taking natural hazards into account in land use planning, and could be liable if damage occurs. In April 2012 the Norwegian government passed a declaration on climate change (MD 2012). Handling of surface water was defined as one of the major challenges that the municipalities in Norway should follow up.

The administration of Trondheim municipality decided to develop a map that shows flood streams which accumulate after heavy rain falls. This map should help to locate where special regulations for the handling of surface water need to be applied.

1.2   Objectives and non-objectives

The objective of the project was to develop a „caution map" (Norwegian: "aktsomhetskart") for flood streams in Trondheim. A "caution map" defines potential risk areas. The map should provide information on locations with a high potential for the development of flood streams after heavy rain on frozen ground. The map should also give an indication of their relative size.

The objective was not to predict the actual areas where a flooding will happen. As well as the exact estimation of water amounts was beyond the scope of the project. In order to judge the actual risk for flooding in detail, more detailed hydrological investigations need to be undertaken.

1.3   Time frame and setting

The project was carried out from 2011 until the first months of 2013. My duty was to develop and execute the GIS analysis in this project. I am mainly working with nature management in the Environmental Department of Trondheim municipality. This project was conducted in the request of the Technical Department for the "Division on Surface and Sewage Water". On workshops supported by "Cities of the Future, Norway", the method and experiences were discussed with GIS analysts and water experts from other Norwegian municipalities.

2   Frame conditions

2.1   Geographic and climatic conditions in Trondheim

Location and topography: Trondheim is situated in the middle of Norway near the coast on a fjord (Figure 5). The administrative area covers 527 km^2, thereof 320 km^2 land area, and reaches from the surrounding fjord to two mountain areas with heights up to 566meters. Two large river systems "Gaula" and "Nidelven" formed flat valleys that extend in the southern and middle parts of the township. The main urban area with around 180.000 inhabitants covers the middle valley and reaches up to the eastern and western slopes. It is crossed by the river Nidelven from south to north. A lot of smaller rivers drain into these two major streams or directly into the fjord. They have their origin in the two mountainous forest areas vest and east from the main urban parts of the town. A total of 27 water catchment areas were determined for streams with an all year around water flow (Figure 3). Some of the water catchment areas exceed the communal border. In (Figure 3) the watershed of the lake "Jonsvatnet" in the south eastern parts of the communal area is drawn to its full extent beyond the communal border.

Geology and soils: The two mountain areas consist predominantly of basalt, which is formed in steep slopes towards the town centre with only a thin layer of topsoil. In the shallow areas towards the big rivers and the fjord, layers of both marine and fluvial sediments accumulated. (NGU 2013 a, b). After the last ice age the melting snow in the inland of Norway caused an ongoing rise of the land masses. This again led to steep river valleys carved into the raising land towards the main rivers and the fjord. Where layers of clay occur on slopes, the risk of avalanches is high – especially after heavy rain falls in areas where the infiltrated water accumulates to a high saturation in soil moisture.

Climate: In spite of the northerly location at 63.25 degree north, just 3 degree south of the polar circle, Trondheim has an overall temperate and humid climate with an average year temperature of 5,3° C and 892 mm precipitation (Figure 4, TRONDHEIM MUNICIPALITY 2013A). This is caused by the closeness to the sea and the effect of the warm Gulf Stream along the Norwegian coast. Situated between the warmer climate in the southern parts of Norway and polar climate in the north, the weather is quite unstable especially in the early and late winter months. The latest knowledge on the consequences of climate change for the middle parts of Norway predicts both rising temperatures and higher precipitation (EDNT 2013).

Flood events: The worst flood events in Trondheim used to happen in late winter, when the ground is still frozen, ice and snow are blocking the manholes and the melting snow accumulates together with heavy rain falls to flooding on the roads.
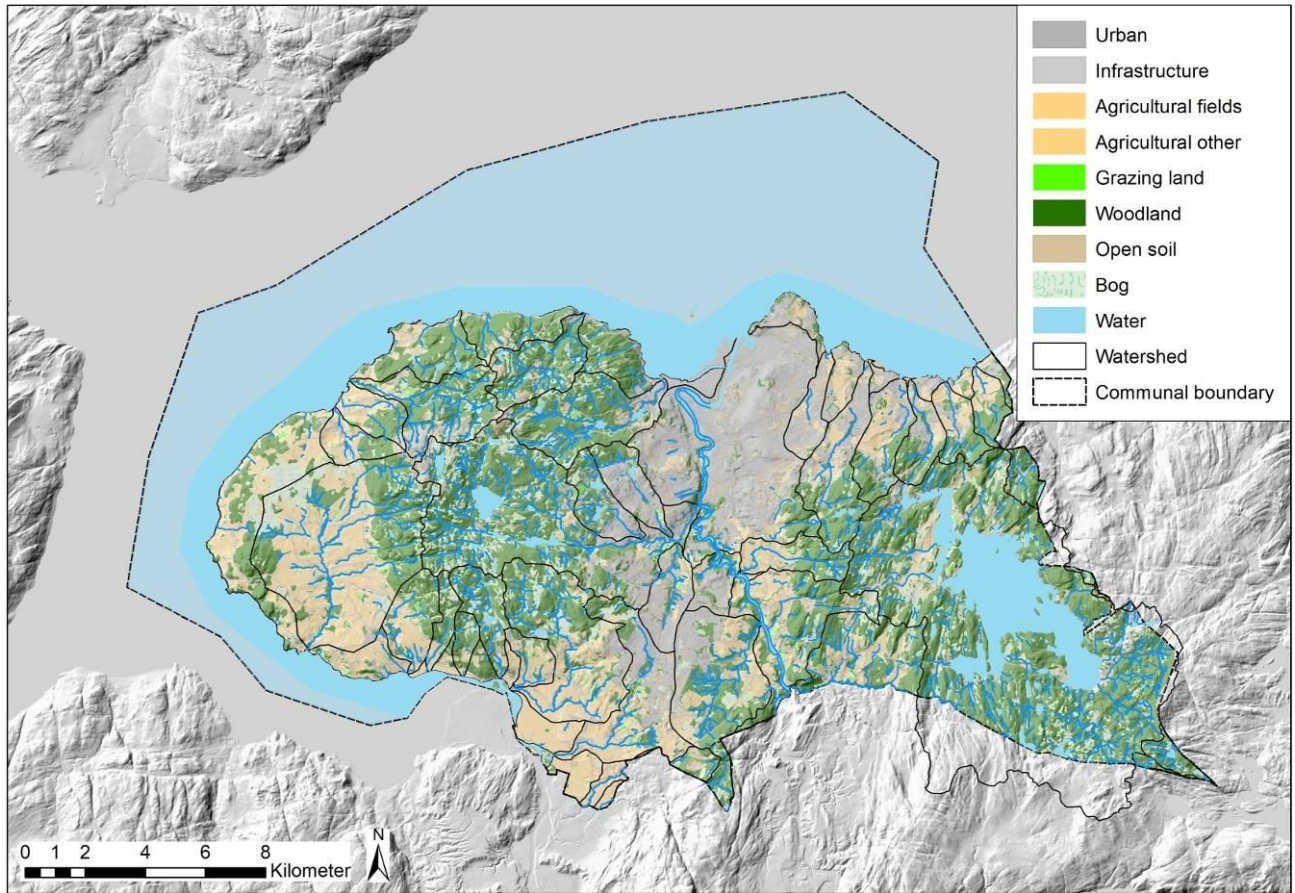

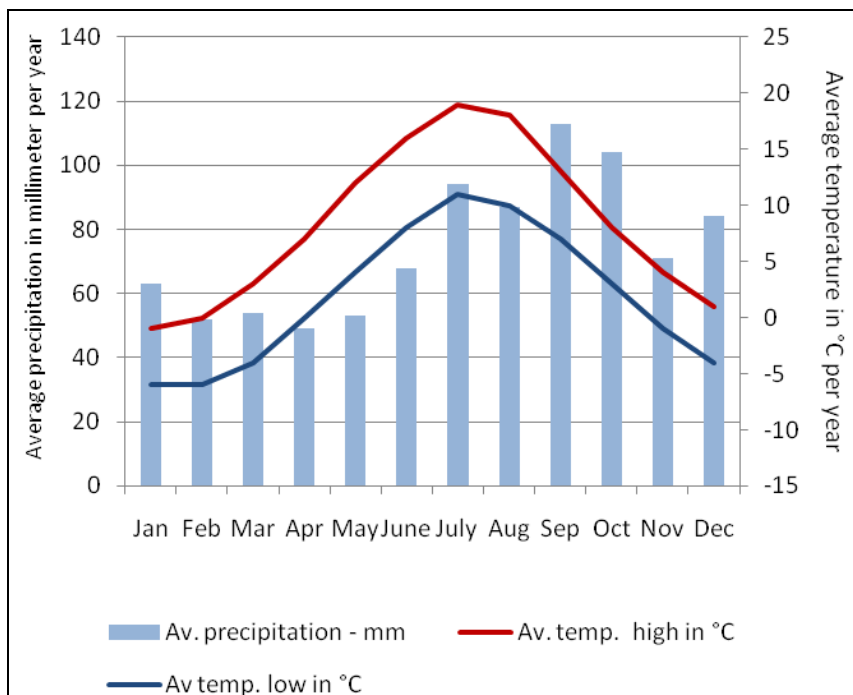**Figure 3**: Topography, community boundary and watershed areas for Trondheim (TM 2012B, SL 2012)

Figure 4: Climate diagram for Trondheim (data from NMI 2013)

Figure 5: Location of Trondheim in Norway (SK 2012)

2.2   Data and other resources

All data used in this project was projected to the following coordinate systems with a 1meter map unit:

- Horizontal: ETRF_1989_UTM_Zone32N
- Vertical: EVRF2007

Laserdata

The height of the ground data for the models in this project is based on laserdata (lidar) taken in summer 2010 for whole Trondheim. While some of the inner parts of Trondheim were taken with a density of 5 point per m^2 most of the area was captured with 2 point per m^2 (Figure 6).

As can be seen in Table 1 the laserdata was poorly classified. While the ground points showed to be very accurate, the class 1 (unclassified) that comprises 12,9% of the data includes a mixture of vegetation, water, buildings and other structures and objects.

The average point spacing for the ground points is 0,97m, which results in about one point per square meter (Table 1). In urban areas with 2pt/m^2 laserdata the ground points show a point spacing average of 0,89m. Even in urban areas with 5pt/m^2 laserdata the average of ground point spacing lies only around 0,82m, due to a large amount of unclassified points for these areas.

The horizontal accuracy of the laserdata is around 10-20cm, the vertical accuracy <=5cm, according to the communal Mapping Department (MELLAND 2013). These measures are valid for objects with a good visibility.

Table 1: Overview over the classification and average point spacing of the laserdata used in this project, determined with the "Point file Information" tool in ArcGIS 3D analyst

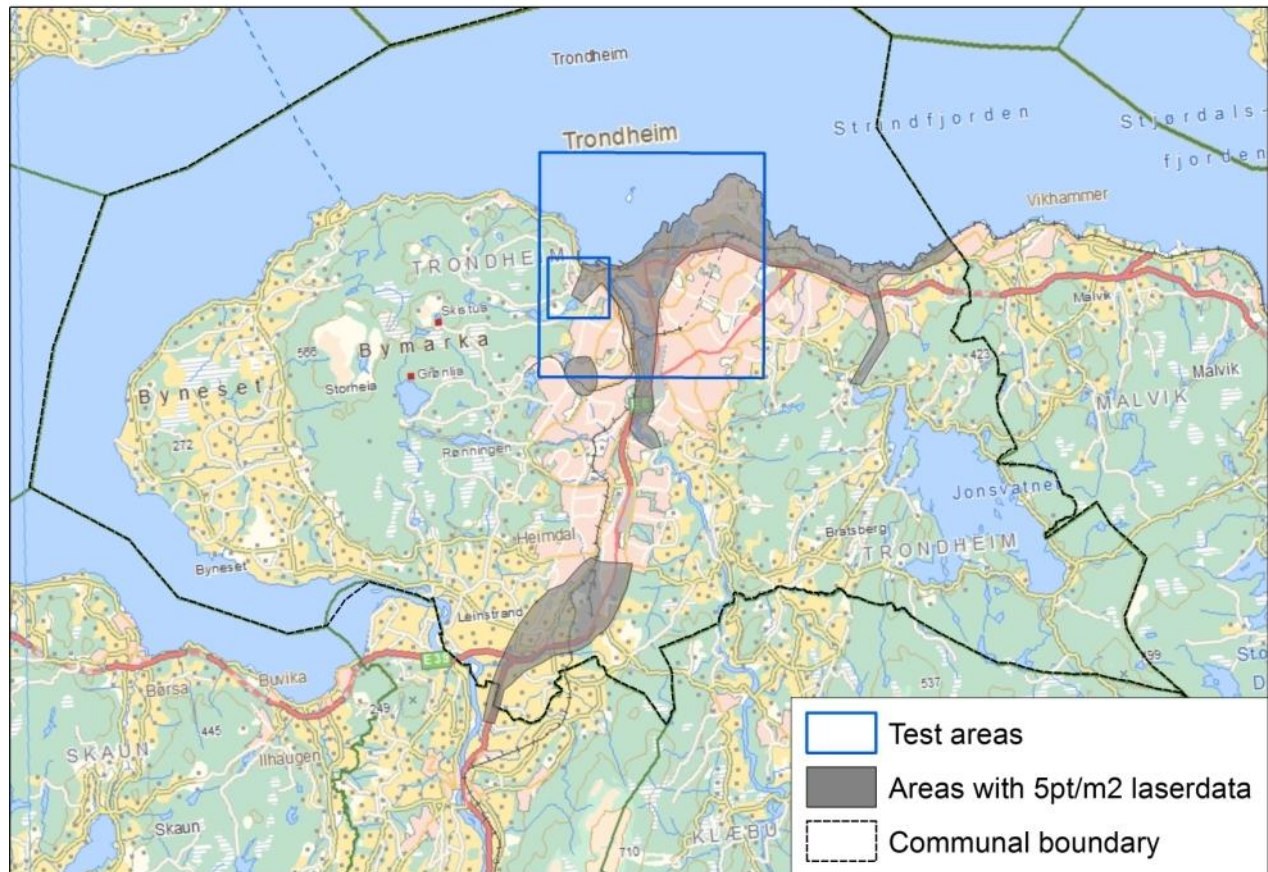| Class	Total amount of points	Amount in percent %	Average point spacing in meter
0 - created never classified	19	0,0	4,99
1 - unclassified	117.075.238	12,9	0,97
2 - ground	739.156.903	81,2	0,96
3 - low vegetation	20.625.014	2,3	5,63
4 - medium vegetation	1.648.164	0,2	18,69
5 - high vegetation	30.297.634	3,3	3,72
6 - noise	1.264.436	0,1	30,52

Figure 6: Test areas and distribution of the 5 pt/m2 laserdata delivered 2010 for Trondheim (Map: SK 2012)

Topographical vector data

The topographical vector data used in this project (see Chapter 4.1) was constructed in 3D by the Norwegian standard "FKB-B", on base of the laserdata from 2010 and orthofotos.

"FKB" stands for "Felles Kartdatabase" and means "Common Map Base" for Norway. It follows the SOSI standard "General feature catalogue" for Norway (NMA 2013). This is the most accurate level of official topographical data available in Norway.

The data is suited for the use in a scale of 1:500. The height accuracy was stated with <= 10 cm horizontally and <= 20cm vertically according to the SOSI Standard.

A first control of the data revealed some inaccuracies with zero-heights that were afterwards readjusted by the delivering company.

Other data sets

A polygon feature class with water shed areas for whole Trondheim was calculated a year before this project based on topographical vector data (see also Chapter 4.5).

For the determination of the slope-layer a Digital Elevation Model (DEM) of 2x2m was used, that was constructed on base of the laserdata and the orthofotos by the company delivering the data for 2010 (Chapter 4.5).

Hard- and Software

For the smaller test areas a laptop with an Intel Pentium II processor, a CPU with 2,1 GHz and internal memory size of 3GB was used. The analysis for the whole area of Trondheim was performed on a laptop with a 64-bit Intel Pentium II processor with 2,6GHz and an internal memory size of 8GB. This machine also reached its limits by building a terrain for the whole area and the conversion into raster format. As a conclusion hardware with a higher performance is recommended for handling similar amounts of data.

The GIS analysis was carried out with ArcEditor 9.3 and the extensions "Spatial Analyst" "3D Analyst".

Partner for collaboration

The project was carried out in close cooperation with two colleagues, Birgitte Johannessen and Olav Nilsson, working in the "Division on Surface and Sewage Water" in the administration of Trondheim municipality. They provided the local expert knowledge on flood events and management of surface water in Trondheim.

During the whole project experiences were exchanged and methods were discussed with Oslo municipality and other municipalities in Norway. Oslo municipality are working on a similar approach based only on laserdata (chapter 6.4).

The laserdata and the basic vector data were obtained by the communal "Division for Mapping and Surveying". They also helped with the publication of the final results in the communal map-application.

For technical support and questions concerning ArcGIS software the support team of "Geodata", the Norwegian ESRI distributor (GEODATA 2013) was consulted.

2.3   Requirements on the process and the result

Requirements on the process: Trondheim is a growing city with a rapidly changing urban area that again influences the run of for flood streams. The process should therefore be repeatable, well documented and based on standard software.

Requirements on the result: The result should be suitable for integration in the local development plan. The accuracy of the map should therefore be sufficient to a presentation in a scale of at least 1:1000 meters. Furthermore the result should be prepared for the presentation as a theme in the map application of Trondheim municipality. The format should allow the combination with other themes and background maps. And the size of the data should provide acceptable loading times for the whole area in the map application.

2.4   Assumptions and scenarios

Two scenarios: In urban areas, the pipe system for surface and sewage water influences the drainage pattern of the flood streams. In Trondheim the major flood events are caused by rainfall in combination with melting snow in late winter when the ducts are partly blocked from ice and snow (Figure 7). The analysis was therefore implemented for two scenarios: A situation where the surface water can pass through the major ducts (>799mm) and a situation where these ducts are blocked.

Drainage factor: The worse-case scenario in Trondheim happens in a situation where the ground is still frozen and can`t hold back any precipitation. The temperatures lie slightly over 0 °C, so that the rainfall will not accumulate in form of snow. Therefore the drainage factor for all surface types was assumed to be at its maximum "1".

Surface water: According to the assumption that the ground is frozen only the flow of surface water is taken into consideration. Infiltration and interflow of groundwater are not considered. Also the effect of seawater pressing into the rivers in a storm flood is not taken into account.

Figure 7: Typical late winter situation in Trondheim, when ice and snow are blocking the ducts and the water accumulates in the roads.

3   Methodical approach

The method for defining and formatting the flood streams consists of five steps, which are visualized in a work flow diagram in Figure 10:

1. Preparing the data

2. Building the height models

3. Defining flood streams

4. Evaluating the result and readjustment of the method

5. Further analysis and preparations for the presentation

In the following, some major considerations and principles for the choice of data, tools, formats and the general approach are described. Details concerning the processing and the workflow are presented in Chapter 4.

According to MOORE ET AL. 1993 the term "Digital Elevation Model" (DEM) is used in this work to describe height models derived only from ground points. Whereas the term "Digital Terrain Model" (DTM) describes a height model which additionally contains constructed features like for example buildings. The "Terrain" format in ArcGIS describes a TIN model comprised of vector data.

3.1   Preparing the data: Choice of vector and laserdata

An important requirement for modelling flood streams is a **hydrological correct height model**. "Hydrologic correct" means the model has been corrected in a way that the calculated flow paths follow the actual streams and flow channels. By adding breaklines that form either barriers or channels to a height model the water can be guided into the right direction. Breaklines also help to correct for errors in the DEM. These errors can be caused for example by a low density of ground points in areas with a lot of vegetation (see also HUTCHINSON 1988).

In order to choose the appropriate data to build the DTM, the following questions had to be answered early in the process: What are the important features that direct the flood streams? From which sources can suitable height data for these features be obtained?

The consulted water experts were quite clear in their statement that besides buildings and other vertical structures, the streets and especially their side edges are important for leading the running surface water through the urban areas (see Figure 8 and Figure 9). In this project breaklines showed to be necessary to model pavement edges in urban areas, to capture linear discontinuities in the surface, lake and sea shorelines and line drains for rivers.

And finally the need to lower bridges, ducts and underground passages evolved during the process. A lowering of these objects in the model was necessary to lead the water through these structures that otherwise would comprise barriers for the water flow. The information for these data was obtained from several sources as described in Chapter 4.1.

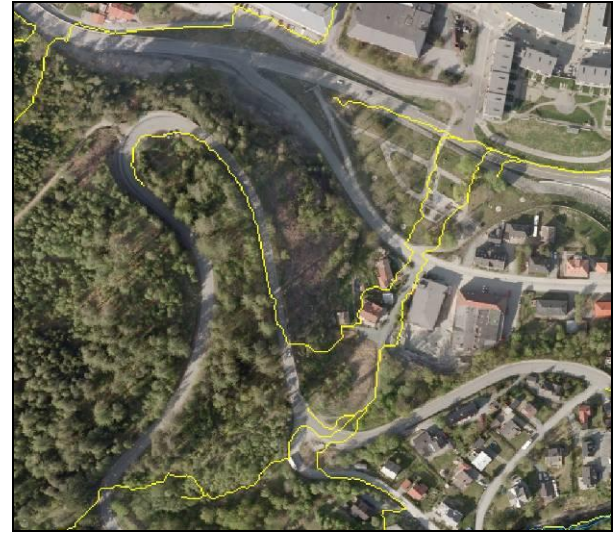**Figure 8:** Flood stream (blue) along a road on a steep hill without pavement edges as breaklines. The water leaves the road too early.

Figure 9: Flood stream (yellow) along a road on a steep hill with pavement edges as breaklines. The water stays on the road and leaves it close to a curve; this corresponds with the field observation.
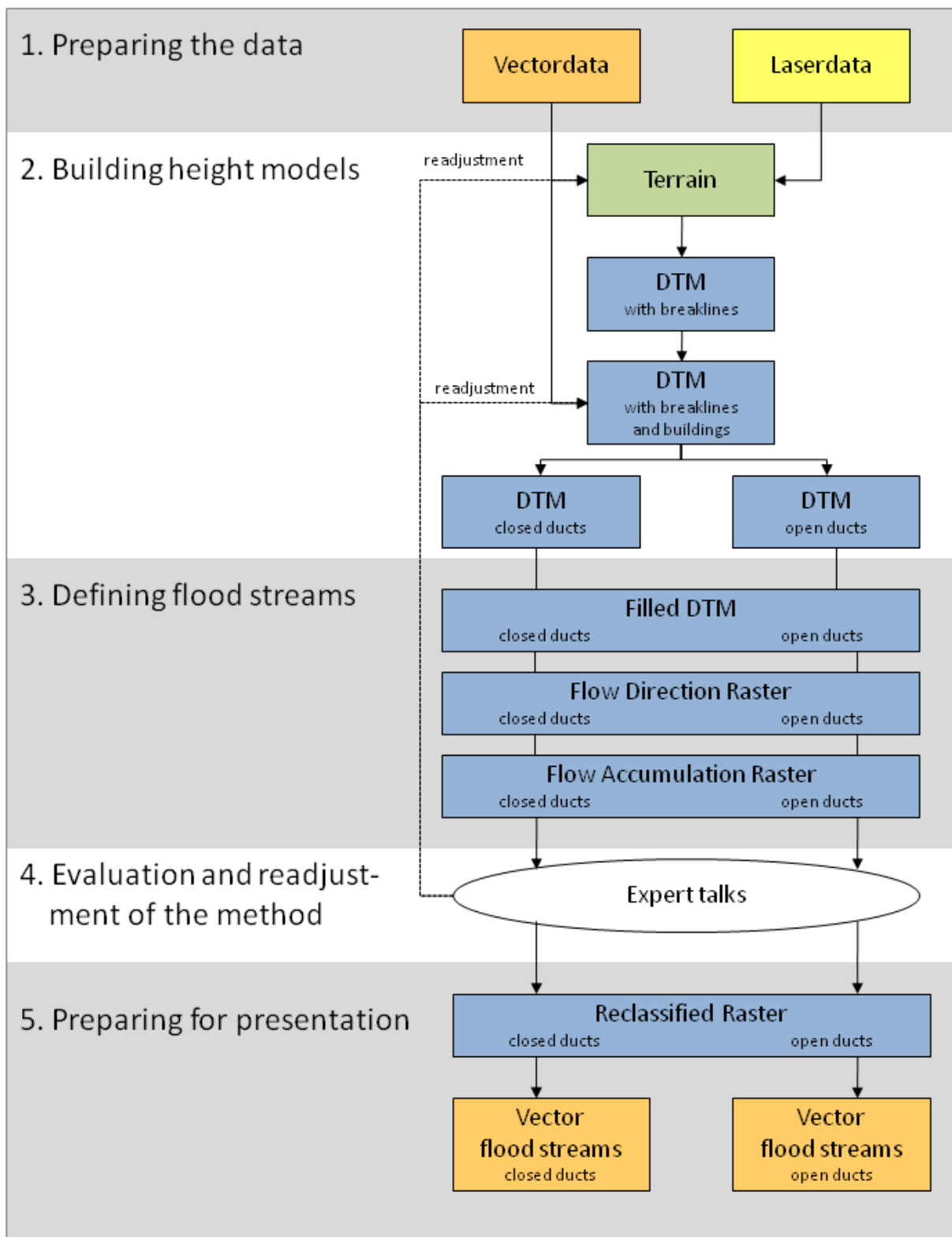
Figure 10: Work flow diagram for defining and presenting the flood streams

3.2   Building the height models: Tools and resolution

Tools
The tools chosen to build the height model had to meet the following requirements:

- They should allow for integration of different user defined data sources (point, line polygon) in defined manners for example as a break line with different height sources (2D and 3D)

- They should allow for the interpolation of height information in areas with low density of ground points, for example in forest areas, were only a few laser points were reaching the ground.

- They should be suited to handle large amounts of laserdata for the whole area.

- They should result in a raster format that can be used for further analysis in Spatial Analyst. Alternatively the result should be convertible to raster format.

- Additionally it would be beneficial if the tool and the format make it easy to apply changes by adding or removing data

In ArcGIS two tools came into consideration for this task: The "topo to raster" tool in Spatial analyst and the "Building Terrain" tools in combination with the "Terrain to raster" tool, bound on the 3D Analyst license. Their performances according to the requirements are compared in the following Table 2.

Simple "Point to raster" or "Feature to raster" tools are not suitable for this task, because they do not provide the possibility to include line features as breaklines and they also lack an interpolation function.

Considering the specified characteristics of both tools in Table 2, the terrain format and a following conversion to a raster was chosen as a method for building the elevation model (DEM). Crucial for this decision were the advantages of the Terrain format to choose variable vector data, the lesser required computing capacity, the easier options to apply changes and the faster presentation of the result together with a visualisation of the used breaklines.

Resolution
Thinking of modelling the edges of streets the first assumption was to take a 0,5 x 0,5m resolution for the height model. An investigation of the laserdata ground points revealed that a resolution of 1x1m was more appropriate to the average point spacing of 0,96m (see Chapter 2.2). Experiments with both resolutions showed that the 1x1m resolution give sufficient results by combining the ground points with the vector data. The coarser resolution also made the handling of the data easier and the analysis faster – an important aspect given the low performance of the available hardware.

Table 2: Comparison of the "Topo to raster" tool and the "Build Terrain" tools. Advantageous features for this process are marked with a ☑ symbol, while disadvantageous features are marked with a ☒.

Require-ments	Topo to raster	Build terrain tools
Integration of different data sources	☒ The vector data that can be included is limited to predefined data types with dedicated formats for integration like for example contour, stream, sinks etc. ☑ Stream data always takes priority over point or contour data. ☑ Height sources from both 2D (columns) and 3D (shape) ☒ No direct integration of lidar data. LAS files need to be converted to multipoint files	☑ User defined data sources (point, line, polygon) ☑ Height sources from both 2D (columns) and 3D (shape) ☑ Breaklines are enforced in the TIN model of the terrain by forming sequences of one or more triangle edges. ☑ Different formats for the integration as so called "surface feature types" can be chosen for example "breaklines", "mass points", "replace polygons" etc. ☑ In ArcMap and ArcCatalog the added breaklines can be visualized on top of the model ☒ No direct integration of lidar-data: LAS files need to be converted to multipoint files.
Interpo-lation	☒ Topo to Raster only uses four input data points for the interpolation of each output cell. ☒ The interpolation is conducted in an intermediate stage before building the raster. This requires a lot of internal memory of the data machine.	☑ A terrain is based on a Triangular Irregular Network (TIN) that uses geodatabase feature classes as data sources. A TIN is constructed by triangulating a set of vertices (points). Because nodes can be placed irregularly over a surface, TINs can have a higher resolution in areas where a surface is highly variable or where more points are available like urban areas and a lower resolution in areas with less ground points like for example forest areas.
Handling large amounts of data	☒ The tool requires a lot of computing capacity, because it is handling all data at once. ☑ Data sources can be stored at different locations.	☑ The presented surface shown in the map is calculated "on the fly" according to the given scale and the chosen thresholds for the pyramid levels. That makes the presentation of large amounts of data fast. ☒ A disadvantage with the pyramids is the smoothing of surfaces for control of the data in larger scales. Therefore suitable thresholds have to be defined. ☒ All source data needs to be stored in one geodatabase in one feature dataset, also the lidardata. That makes the geodatabase big and difficult to manage.
Output format	☑ The topo to raster analysis produces a raster format that can directly be used in Spatial Analyst	☒ The resulting terrain format has to be converted to raster format in order to use it with Spatial analyst. (Tool "Terrain to raster")
Apply changes to the model	☒ In order to facilitate the application of changes an output parameter file has to be created in the Topo to Raster dialog box. This file can be modified in a text editor and used as input to the "Topo to Raster by File" tool. This approach is quite complicated.	☑ The tools for " Add / remove feature classes from the terrain" allow an easy adding or removing of feature classes

3.3   Defining flood streams: Hydrological analysis

According to the objective (Chapter 1.2) the resulting map should locate potential areas where flood streams can develop and give an indication of their (relative) size. In this chapter the basic principles for the hydrological analysis are described. Details for the processing are presented in Chapter 4.

Overview over the hydrologic analysis

The method used for this project is based on a hydrologic analysis of the flow of water across a surface. Therefore the runoff characteristics from each cell in the height model needs to be determined. Once the direction(s) of flow out of each cell is (or are) known, it is possible to determine which and how many cells flow into any given cell by a so called flow accumulation analysis. This information can be used to define watershed boundaries and flow channel that can be further analysed to stream networks. The relative size of a flow channel is indicated by the amount of upwards cells draining into it. In this project a "flood stream" is defined as a flow channel with an upward catchment area above a defined threshold value. The hydrological analysis in this project was carried out in four steps (Figure 10) that are further discussed below:

1) Generate a depressionless DTM where all sinks are filled, to secure a continuous flow of water through the model.

2) Calculate a flow direction raster from the depressionless DTM.

3) Calculate a flow accumulation raster that indicates the amount of all "upslope" cells floating into each cell.

4) Identify flood streams as cells which flow accumulation value lies above a defined threshold value. This raster was afterwards reclassified and converted to line features.

The results are flood streams in form of line segments with a value indicating the size of the water catchment area draining into each line. This format fulfils the objectives in this project. But it also comes with limitations:

- Flood streams used to become a problem when a lot of water accumulates within a short time period. The values created by the flow accumulation analysis only show the static size for the whole catchment area for one cell.

- The results of this analysis are only two-dimensional lines while in reality the flooding water spreads over a three-dimensional area. The affected area can only be deviated indirectly by the size of watershed and slope and sinks close by. Approaches to determine the dispersion of the water are presented in Chapt. 6.2.

Further hydrological analysis allows the building of a stream network. For the objective of this project the building of a network was not necessary. Instead of defining the order of the streams it was more important to preserve the information of the size of the water catchment area through a user defined reclassification.

The need to generate a depressionless DTM

A sink in a height model is defined as a cell that is surrounded by higher neighbouring cells (see Figure 11, PEUCKER & DOUGLAS 1975). A flow channel that flows into a sink is "trapped" and will not continue. When a sink is filled, the flow channel can continue down slope. In a depression area the filling of a sink can generate a new sink area that again has to be filled.
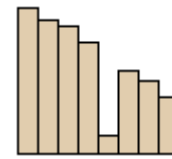

Figure 11: Profile view of a sink (ESRI 2012B)

This filling process is conducted to the pour point of the depression which locates the overflow on the minimum elevation along its watershed boundary. A "depressionless" DTM where all unwanted sinks are filled is a precondition for a flow accumulation analysis. FREEMAN (1991) gives an overview over several methods that where developed to fill sinks that differ in the way they model the runoff characteristics of the new surface of a filled depression. By defining a maximum height to which sinks should be filled, the user can preserve the effect of deep real sinks in the terrain.

During the winter scenario in Trondheim with a thick layer of ice and snow on the surface it is likely that most of the depressions are fully filled to the pour point. The method used to locate the depths of sinks is described in Chapter 4.5.

Algorithms for the flow direction

Several algorithms to define the flow direction have been developed. In 1984 O'Callaghan and Mark (1984) conducted pioneer work by introducing the deterministic 8-neighbour (D8) algorithm.

Based on the elevations within a 3 by 3-pixel window, the D8 algorithm assigns one flow direction from the central cell in the direction of the steepest drop to the neighbouring cells. The output value is based on an eight direction (D8) single flow model, shown in Figure 12.

Figure 12: Principle for coding the flow direction in the D8 Algorithm (ESRI 2012B)

The advantages of this algorithm are based on its simplicity and its clear deterministic approach by assigning the runoff to only one neighbouring cell. It is well suited to derive a line network of flow channels and the determination of water catchment areas. Therefore this algorithm is widely used.

But it comes also with some conceptual inaccuracies (DUKE ET AL. 2003):

- The reduction to only one flow direction from each cell leads to inaccuracies on areas where the water flow disperses, for example on flat areas and homogenous slopes.

- The limitation to eight directions results in an unnatural guidance of the water flow into predefined angles.

- The algorithm also shows the tendency to produce parallel flow paths in flat areas.

- The algorithm fails in representing flow accurately on convex slopes.

- And it shows sensitivity to small errors in the height model.

Consequently further algorithms to determine the flow direction were developed. A comprehensible description of seven algorithms is given in CONRAD (1998). Two dimensional algorithms allow the simulation of a diverging run off into several directions. CONRAD (1998) conducted a comparative test on seven algorithms in which the two dimensional "Multiple flow direction" algorithm performed best (Figure 13). In this algorithm the flood streams are divided proportionally to their declination towards the source cell. Depending on the relief situation the resulting runoff can be highly diverged. A slightly similar approach is used in the D-infinity algorithm, which is widely used and performed as the third best in this test. This algorithm portions flood streams that fall between the direct angles of two adjacent neighbouring cells, according to how close the flow direction angle lies to the direct angle to those cells. The flow can occur between 0 and 360 degree and is described as a line in the direction of the gradient. This algorithm shows a lesser dispersion than the Multiple Flow Direction algorithm.

Because the drainage directions for all these algorithms are based only on elevation values, their accuracy depends highly upon the quality of the height model.
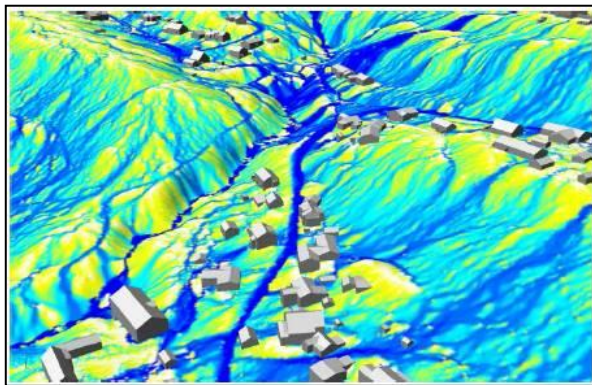

Figure 13: Multiple flow flood streams calculated in GRASS with the D.-infinity algorithm of r.flow (NEM N.D.)
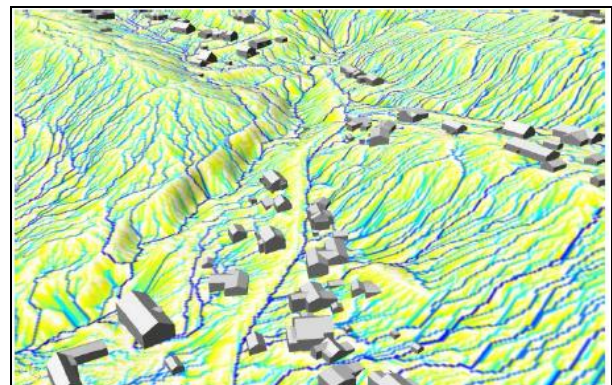
Figure 14: Single flow flood streams calculated with the D8 algorithm (NEM N.D.)

Methods to determine the Flow Accumulation

The flow accumulation function calculates the accumulated flow of all cells draining into each downslope cell in the output raster (see Figure 15). By applying a weight factor it is possible to simulate differences in the drainage caused for example by differences in the runoff characteristics of land cover types.
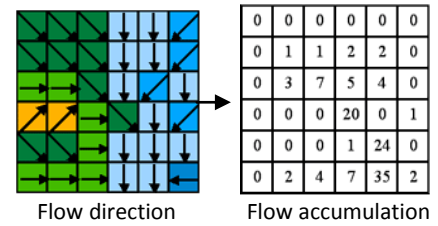
Flow direction   Flow accumulation

Figure 15: From Flow direction to Flow accumulation (ESRI 2012b)

In this project no weight factor was applied in order to simulate a winter scenario with rainfall on frozen ground that will not hold back any surface water. The resulting value reflects therefore the number of cells that flow into each cell, which allows for a determination of the water catchment area.

Hydrology tools in ArcGIS

ArcGIS is the main GIS software used for analysis in Trondheim municipality. Given the requirement that the method should be easy to reproduce, it was consequent to use the ArcGIS Hydrology tools as a first choice for the analysis. The building of the height model became so time consuming that there was not enough capacity to try out other or supplemental programs and extensions.

The hydrology tools in ArcGIS Spatial Analyst comprise of several tools that are building up on each other as can be seen in Figure 16. For this project a flow accumulation raster was determined using the tools: "Flow direction" "Sinks", "Fill" and "Flow accumulation". The building of a stream network was not necessary as discussed before. The tools for defining watershed areas were already used in an earlier project to calculate the watershed areas as described in Chapter 4.5.

The advantage with the hydrology tools in ArcGIS are their user friendly operation interface, the possibility to choose several settings and environments for the analysis (see Chapter 4.3) and the possibility to integrate the tools in the Model builder. That eases the documentation and the application of changes and iterations during the process.
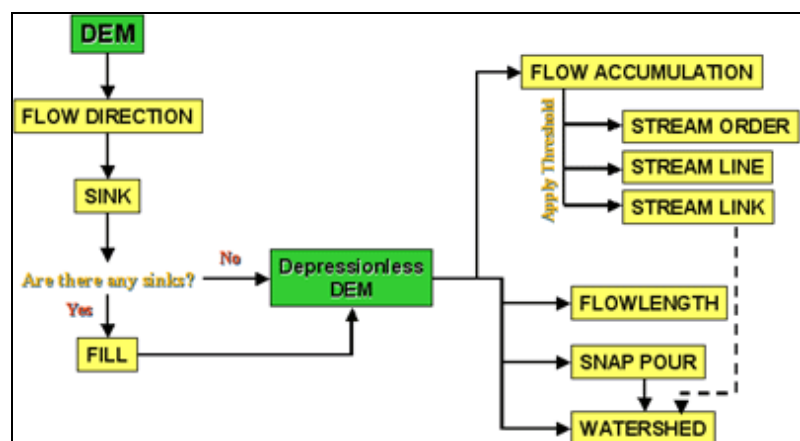
Figure 16: Work flow diagram of the Hydrology tools in ArcGIS Spatial Analyst (ESRI 2012a)

The main disadvantage of the hydrology tools used in this project is the limitation of the flow direction tool to the D8 algorithm. The consequences for the result are further described in Chapter 5.

3.4   Development of the method within smaller test areas

The integration of vector data for building the height model required a lot of decisions. These were defined in an iterative "circled" process with the steps: assumption – processing – evaluating – new assumption. In order to facilitate this process, the development of the method was carried out within two smaller test areas, before it was applied to whole Trondheim (Figure 6).

The location for the test areas were chosen by several criteria. They had to cover:

- Both steep and flat slopes,
- minor to major creeks,
- bridges and major ducts,
- urban parts as these are the most critical for flooding and
- areas with both 5 and 2 laser points per square meter.

4   Processing and analysis

The processing and analysis follows the same steps described in Chapter 3. In this chapter practical considerations for the implementation are presented, like the choice of settings in the analysis and the preparations for the presentation in the communal map web application.

4.1   Preparing the data

Preparing the laser data (lidar)

In order to integrate the lidardata in a terrain, they needed to be converted to multipoint format and imported into a geodatabase as a feature class together with the other vector features. The conversion was conducted with the "LAS to Multipoint" geoprocessing tool. The following settings were chosen:

- Class Code: Only ground points, class 2, were chosen. Unfortunately the laserdata was not good enough classified to distinguish buildings from cars, vegetation and other 3D features, so that these features had to be constructed from vector data.

- Average Point spacing: According to the "Point file information analysis" the average point spacing for ground points (the class 2) was set to 0,97m.

- Return: Because the selection was already restricted to ground points, "ALL RETURNS" were chosen.

Lessons learned

- Be clear when ordering laserdata on the classification required. Based on the experiences of this project, I could contribute with requirements for the order of new laserdata taken in 2013.

- Control the classification of the laserdata after receiving the data - especially the classes cars <> buildings and buildings <> vegetation are often not properly separated. This was also an experience from the municipality in Oslo.

- When dealing with laserdata it is useful to learn how to use FME – it makes handling of huge amounts of laserdata a lot easier.

Preparing the vector data

The coarse resolution of the laser data and the lack of its classification made it necessary to use vector data to refine the height model according to hydrological requirements. The following features were prepared for integration in the height model:

    a. A clip polygon feature

    b. "Breaklines" from water and street features

    c. "Hard clip areas" from water surfaces

    d. Footprint areas from buildings that needed to be raised

    e. Polygons that cover bridges and ducts that needed to be lowered

a) A **clip polygon feature** was prepared including the extent of the land-surface area of Trondheim. Ideally the height model would cover the complete area of all water basins that drain into Trondheim. Unfortunately the laserdata was only provided for the administrational area of Trondheim, so that the height model analysis was restricted to this area. An approach to enlarge the height model on another database is presented in Chapter 6.2.

b) **Breaklines** are used in digital elevation models to add linear features that are not sufficiently represented by the lidar data and to form a hydrologic correct height model as described in Chapter 3.1. The choice of the right data for break lines was a trial-and-error-process conducted within the smaller extends of the test area (Figure 6). Selected line features of both street- and water themes were chosen. According to the data source these were (the names are in Norwegian, representing the standard format for Norwegian FKB-data):

- Water lines: "OBJTYPE" IN ('ElvBekk', 'ElvBekkKant', 'ElveElvSperre', 'Innsjøkant', 'KanalGrøft', ' 'KanalGrøftKant' Kystkontur', 'KystkonturTekniskeAnlegg')
- Street lines: "OBJTYPE" IN ('AnnetVegarealAvgrensning', 'Fortauskant', 'FortauskantYtre', 'GangSykkelvegkant', 'GangfeltAvgrensning', 'Gangvegkant', 'Lysløype', 'ParkeringsområdeAvgrensning', 'Sti', 'Trafikkøykant', 'Traktorveg', 'Vegdekkekant', 'VeggrøftÅpen', 'VegkantAnnetVegareal')

The chosen lines were clipped to the extent of the clip polygon feature. Afterwards the height information stored in the "shape" column was visually controlled in ArcScene with 3D analyst.

c) **Water areas** like lake and sea surfaces were added as "hard clip" to the terrain. The lidar data shows rough surfaces on the water areas that could be smoothed with plane water polygons. The height information for the water bodies had to be combined from different columns in the original data.

d) **Buildings:** A polygon with foot stamps of buildings was used to raise the buildings 15m above the surface, in order to force the water to flow around. This was necessary because the lidar data was not sufficiently classified to distinguish between buildings and other features like cars. The following themes were chosen:

- Building polygons: "OBJTYPE" IN ('Bygning', 'AnnenBygning')

It would have been more elegant to use the real heights for the buildings, but this would have been more complicated due to varying roof-heights. In order to raise the buildings 15m, a column was added with the constant value 15 and was used in the conversion with the "Polygon to raster" tool as a value field. "No data" values needed to be reclassified afterwards to "0" values.

e) **Bridges and ducts:** Bridges and ducts had to be lowered in the height model in order to give the water the possibility to flow under or more precisely "through" (Figure 17and Figure 18). The composition of a polygon dataset for bridges and ducts was very time consuming, due to a lot of different sources that had to be integrated:

- Sources for bridges (567 objects): Information for the bridges could partly be taken from the vector data for streets, but most of the bridges had to be manually digitized from aerial photographs.

- Sources for ducts and underground passages (1277 objects):
  - Vector data for streets marked as underground passages;
  - Data from the Directorate for Railroads and Streets;
  - Surface-water pipes registered in the water database of Trondheim municipality;
  - Manual editing of streets crossing waterways from aerial photographs;
  - An intersect analysis of a creek / river polygon feature with a polygon feature for streets. Because creeks flowing parallel to rivers often gave wrong results, the resulting polygons were sorted out: Only the intersections larger than 3 m^2 with a thickness ratio > 0,05 were selected.

The diameter of ducts to be chosen for lowering the height model had to be defined in the evaluation process together with local experts (Chapter 4.4). Finally a diameter of >799mm for the ducts was regarded as appropriate for the hydrological adjustment of the model.

Both bridges and ducts were applied buffers in order to cover side features like footpath and balustrades that otherwise would stick out as a barrier for the water. The buffers needed to be adjusted individually for most of the bridges. Height columns with constant values were added to the polygon features (25 for bridges and 10 for ducts). All the features were merged to one polygon layer with one height column. This height column was taken as the value field for converting the polygon to raster format. "No data" values needed to be reclassified afterwards to "0" values.
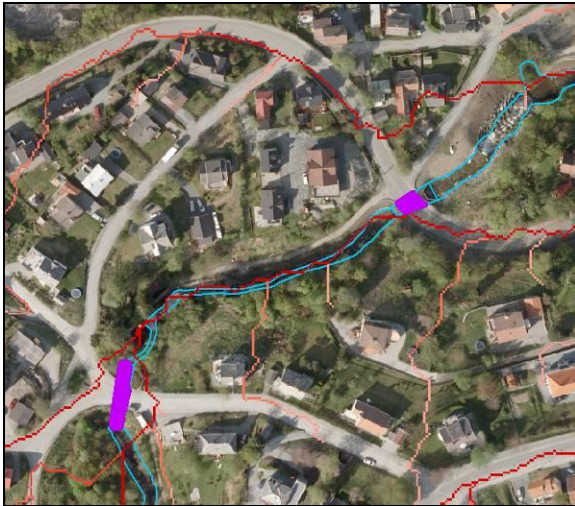
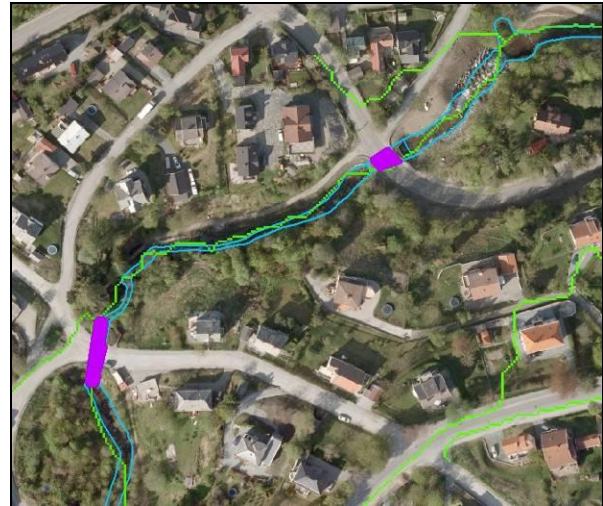**Figure 17:** Flood stream (red) without lowering bridges and ducts (purple)

Figure 18: Flood stream (green) after lowering bridges and ducts (purple)

Modelling flood stream for two scenarios:

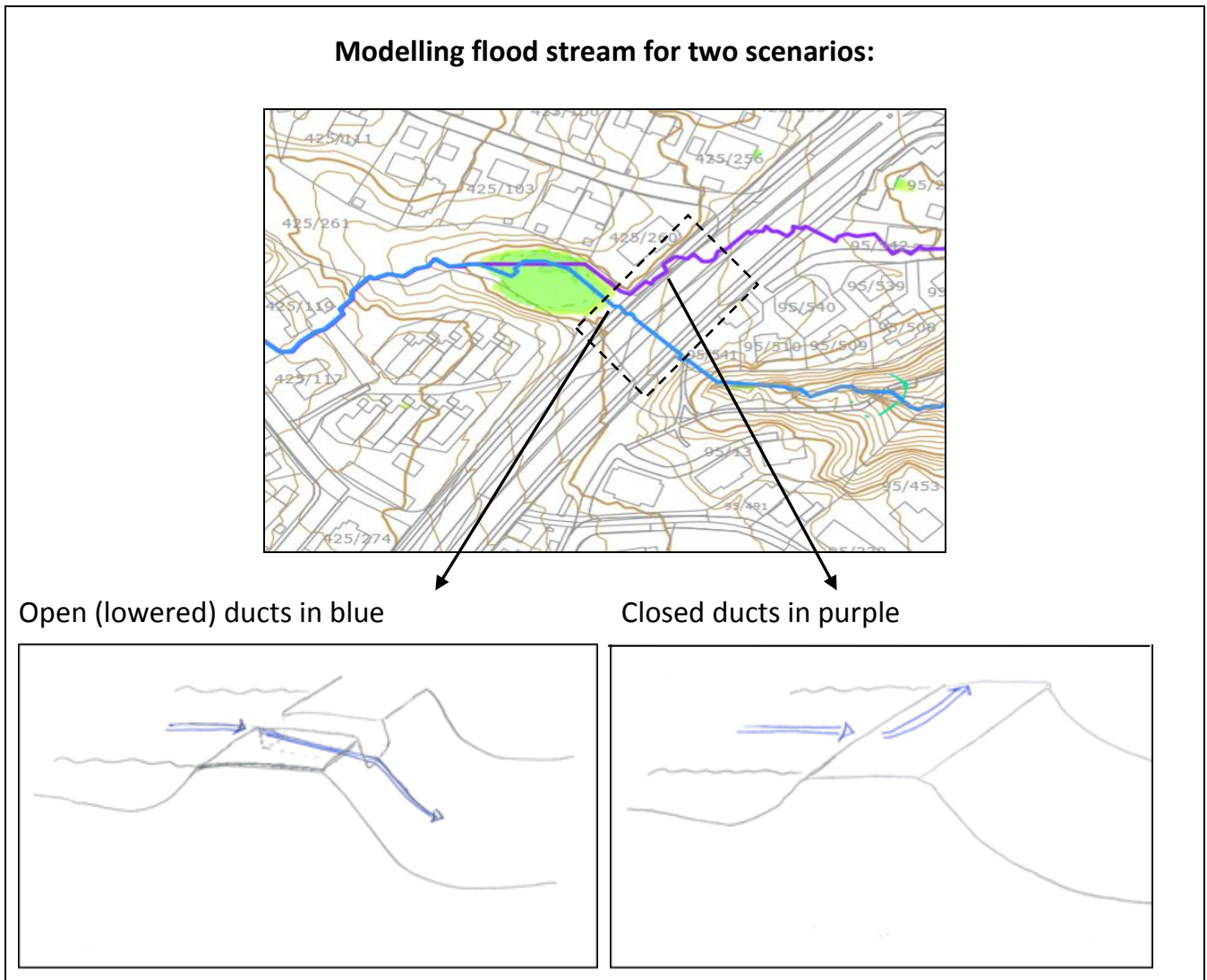Open (lowered) ducts in blue   Closed ducts in purple

Figure 19: Principle for modelling the two scenarios: Open and closed ducts.

Lessons learned

- Always check the height information after clipping a data set. The clipping can change the height information at the edges to "No Data" or "Zero". Therefore the clip feature should be larger than the area of interest.

- Document all steps of the process in ArcGIS Modelbuilder. This makes it easy to go a step backwards and change settings.

- If you need to use a tool for many features simultaneously for example the "clip to polygon" function, you can save a lot of time by defining a parameter for the input variable as a "list of values".

- It is important to expand the features that you want to lower with a buffer to the sides facing the water. Otherwise side structures like balustrades might stand out as barriers for the water flow.

- But be careful with adding a buffer to the side of bridges. You might create an unwanted passage for the water in the direction of the bridge. Only lower the area that directly lies under the bridge passage (Figure 21).

- Be careful with lowering underground passages. There might be a flood stream on the road above that is more important. When you lower the passage, you will misguide this flood stream in a wrong direction (Figure 20).
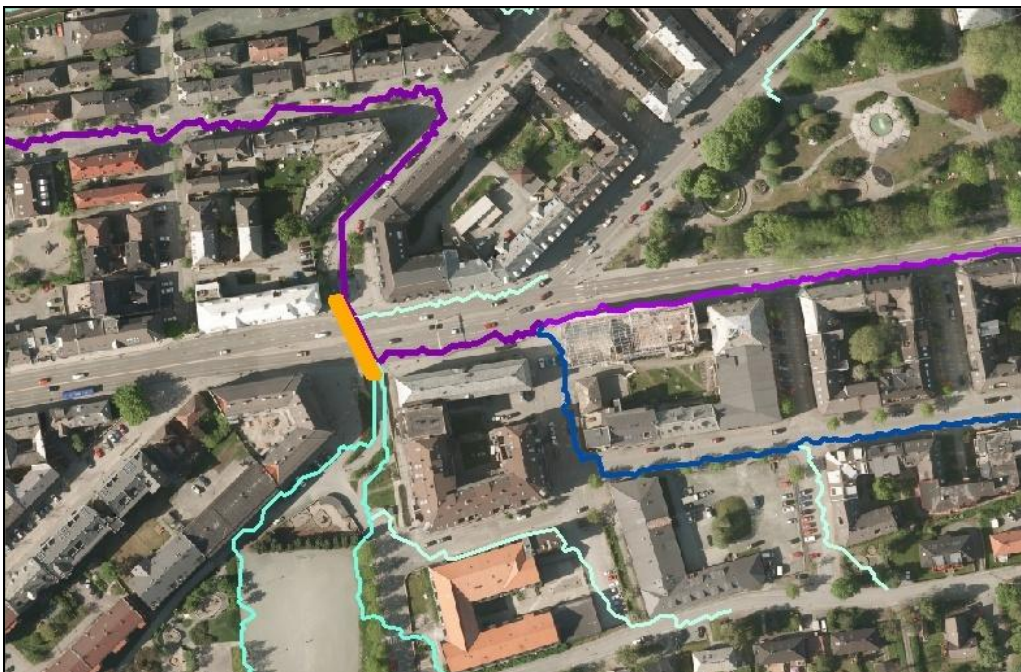
Figure 20: Underground passages (orange) must be reviewed individually before lowering them to guide the water through. There might be a more important flood stream on the road above (purple).
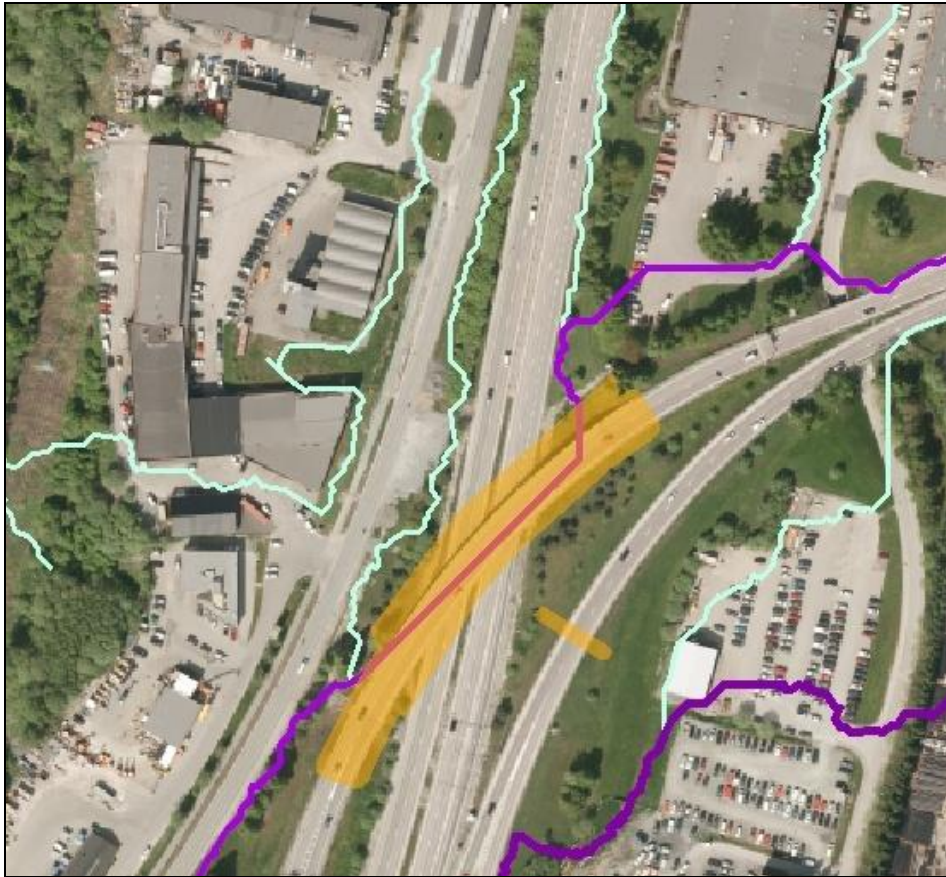
Figure 21: Be careful with adding a buffer to the side of bridges. You might create an unwanted passage for the water in the direction of the bridge. Only lower the area that directly lies under the bridge passage.

4.2   Building the height models

The building of the height models used for the hydrological analysis was conducted in four steps that are presented below. In order to improve the readability of the presented rasters, both a hillshade effect and a gammar stretch of 1,5 were applied.

1) **Build a terrain** with the lidar ground points and the vector data described in Chapter 3 with the "terrain wizard" (ESRI 2012c).
    - BREAKLINES: Line features from streets, constructions and water objects,
    - MASSPOINT: Laserdata converted to multipoint format,
    - HARD REPLACE: Polygons for lakes and the sea
    For the pyramids a z-tolerance filter was used, which is most effective with lidar ground points (ESRI 2012d)

Figure 22: Terrain with applied breaklines

2) **Convert the terrain to raster** format with the "Terrain to raster" tool.
    - DATA TYPE: "Float" was chosen in order to preserve minor height differences for example for pavements,
    - INTERPOLATION METHOD: The Nearest Neighbour Interpolation was used in order to preserve small scale differences in height for example the edges of streets that were added with breaklines,
    - CELLSIZE: A raster size of 1x1m was chosen as explained in Chapter 3.2.

Figure 23: Digital Elevation Model (DEM)

3) **Raise buildings**
    The building raster with the value "15" for buildings was added to the DEM raster with the "Plus" tool in Spatial Analyst.

Figure 24: Digital Height Model (DTM) with raised buildings

4) In this final step **two versions of DTMs** were created:

DTM 1 with lowered bridges (25m) - for the version with closed ducts

DTM 2 with lowered bridges (25m) and selected underground passages and ducts (10m)- for the version with the open ducts

Both analyses were conducted by using the "Minus" tool in Spatial Analyst and the corresponding raster layers prepared from polygon data for bridges and ducts as described in Chapter 4.1.
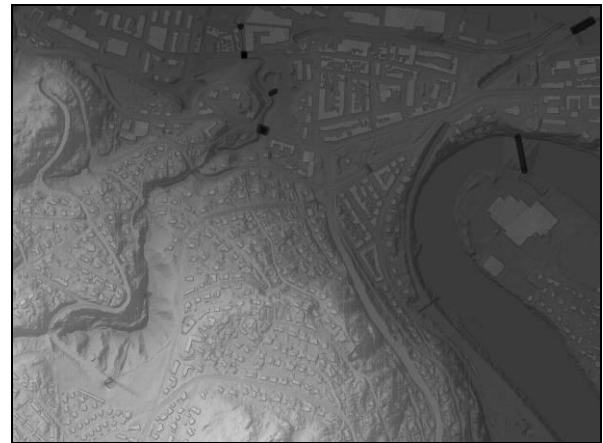

Figure 25: DTM with raised buildings and lowered bridges and ducts shown as "black hoes"

Lessons learned:

- Don`t try to copy a terrain dataset without the belonging feature classes. And you also can't copy feature classes that participate in terrain datasets. Instead, choose to export or select. (Typical beginner mistakes, but they helped to understand how the terrain format is working.)

- For line features always use 3D data with "shape" as a height source. If you take the height information from a column, a whole line object only receives one height, which results in a stair-like appearance of for example street edges or river beds. The only exceptions were you can use height from columns are boundaries for lakes or sea shores defined on an equal height level.

- Integrate laserdata in the terrain format only as multipoints not as single points. In the beginning of the project, I asked the mapping department for point data from laser. I received a single-point dataset for my test area, produced with other software. The calculation took ages and the resulting terrain was very unstable.

- By using the "Minus" and "Plus" tools in Spatial analyst, make sure that all the raster layers cover the whole area. Otherwise the resulting raster will be reduced to the smallest layer.

4.3   Defining flood streams

The analysis to define flood streams was carried out in four steps on base of the resulting two DTMs from Chapter 4.2 (with "open" and "closed" major ducts). The basic principles and functioning of the applied tools were already described in Chapter 3. In this section the chosen parameters for the analysis are explained. The intermediate raster figures presented in this chapter are based on the DTM for a scenario with open ducts (DTM 2).

1. **Depressionless DTM**
   Tool: "Fill" in Spatial Analyst

   FILL LIMIT: A visual evaluation of the sink areas showed that the location and size of the sinks were mainly correct, when completely filled (see also Chapter 3.3). Therefore no fill-limit was applied. The depths of the sinks were calculated according to the method described in Chapter 4.5.

Figure 26: Depressionless DTM after filling the sinks

During the fill procedure also "holes" that were generated by lowering bridges and ducts were filled to the ground level. This can be seen by comparing Figure 26 to Figure 25.

2. **Flow Direction Raster**
   Tool: "Flow direction" in Spatial Analyst

   FORCE FLOW: With this parameter it is possible to force the flow at the edges of the surface area to go outwards. The water catchment areas in the south and east of Trondheim exceed the communal boarder with streams flowing into Trondheim. Therefore this parameter was set to "NORMAL", also allowing an inward flow from outside the DTM area.

   A DROP RASTER was calculated to evaluate the flow direction in flat areas.
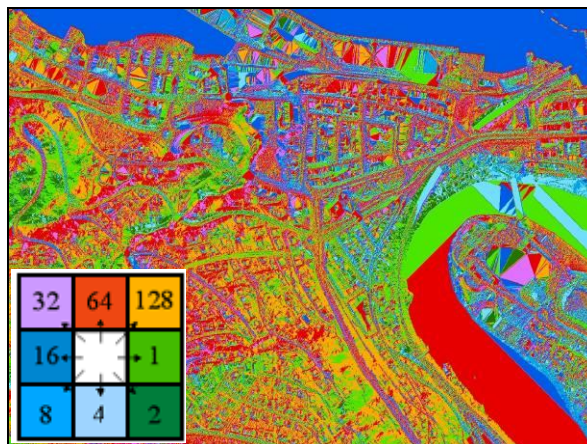
Figure 27: Flow Direction Raster created from the depressionless DTM with lowered bridges and ducts. The diagram shows the colour code for the directions.

3. **Flow Accumulation Raster**
   Tool "Flow Accumulation" in Spatial Analyst

   WEIGHT FACTOR: For this analysis it is possible to apply a raster with a weight factor for the drainage of each cell. According to the assumption of a maximum drainage factor for each cell on frozen ground (Chapter2.4) no weight factor was applied, so that the default value 1 was used.
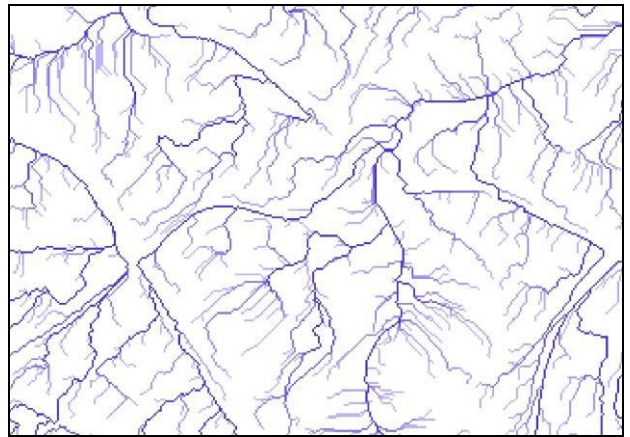

Figure 28: Flow Accumulation Raster for a minor area; values < 50 are set to white colour.

4. **Identifying flood streams**

   Based on the Flow accumulation raster a flood stream is a line of adjacent raster cells with a high value for the flow accumulation and accordingly a certain size of watershed area. The challenge was to identify the threshold value for identifying a flood stream.

   Hydrological considerations: To identify this threshold the water experts analysed earlier flood events in urban areas in Trondheim and corresponding measurements of amounts of water in litre/second*km^2. A range of measurements were transferred to the m^2-values of the flow accumulation raster and the result was visually assessed. Bearing in mind the fact that these flood streams should be the base for regulations on new construction sites, a quite high threshold was defined, to only cover the flood events that are likely to cause problems. The outcome of this process was the following statements:

   - Earlier flood events in urban areas showed, that flood streams tend to become a problem from a water amount of at least 2.000 l/s*km^2

   - Major flood events in urban areas in Trondheim arise with a water flow of at least 100l/second. This number refers to measurements taken in small rivers in Trondheim, where the amount of water flow is measured in litre per second.

   - By following the equation: 2000l/1s*1.000.000 m^2 = 100l/1s* ?? m^2, this results in a critical water catchment area in urban areas of at least 50.000m^2 for defining a flood stream.

   In addition, the field assessment showed that in non-urban areas like for example parks and forest, flood events may become a problem with a lesser catchment area of already 25.000m^2. This is caused by the fact that in urban areas the drainage pipe systems drains off a part of the surface water. In order to compensate for this effect in the presentation, the flood streams with a size from 25.000 to 50.000 m^2 can alternatively be added to the map by the user. An option to account for this effect already in the analysis is discussed in Chapter 6.3.

Creating vector maps to facilitate the process:

In order to visualise different threshold values for the catchment areas on a map, the two flow accumulation raster (from DTM1 and DTM2) were converted to polylines with the tool: "Raster to Polyline".

In the first try of a direct conversion from the original raster values it became apparent that the values for the water catchment areas exceeded the maximum allowed size of six number-spaces for the output value in this tool. In order to preserve the information of the water catchment areas and to reduce the amount of resulting features, the raster was in a first step reclassified in 11 classes (tool: "Reclassify") before the conversion to vector format.
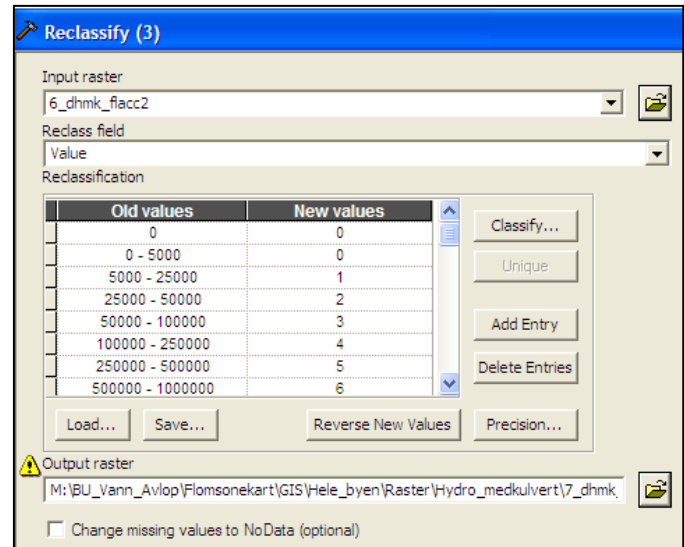
Figure 29: Settings in the „Reclassify" tool window

After defining the two threshold values 25.000 and 50.000m^2 the vector layer was again reclassified to 6 classes in order to facilitate the readability of the map. There exists no pre-defined tool in ArcGIS 9.3 for reclassifying vector data. This task was solved by writing a simple Python script for the "Calculate Field" tool (Figure 30). Alternatively it would have been possible to go back and modify the reclassification in the raster format. But the script provided a solution in vector format that could also be used for other tasks.

```
def Reclass (GRID_CODE):
 if (GRID_CODE >= 1 and GRID_CODE<= 1):   return 0
 if (GRID_CODE >= 2 and GRID_CODE<= 2):   return 1
 if (GRID_CODE >= 3 and GRID_CODE<= 4):   return 2
 if (GRID_CODE >= 5 and GRID_CODE <= 6):   return 3
 if (GRID_CODE >= 7 and GRID_CODE<= 8):   return 4
 if (GRID_CODE >= 9 and GRID_CODE<= 11):   return 5
```
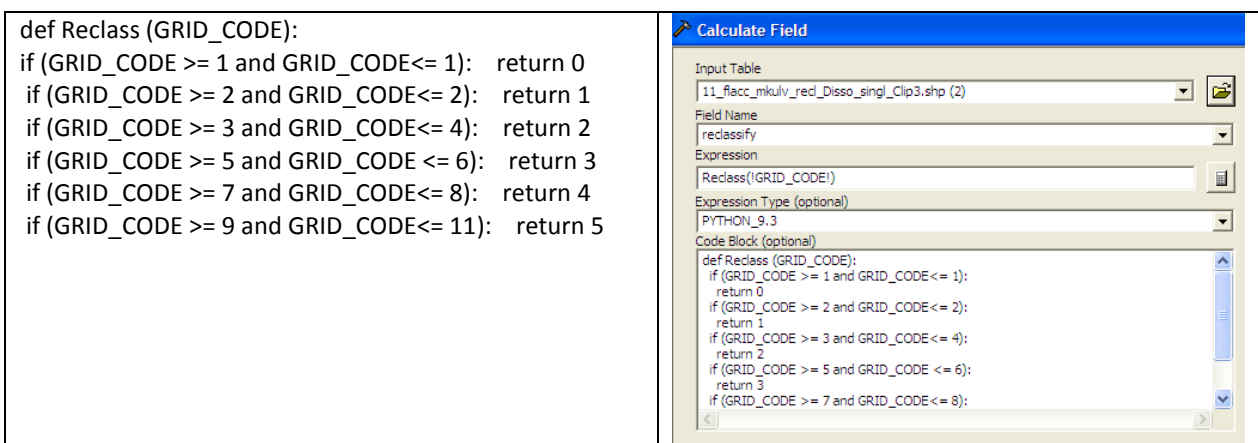

Figure 30: Extract of the script used for the „Calculate Field" tool, which is shown on the right

Lessons learned

- In the conversion tool „Raster to Polyline" there is a limit of six number-spaces for the output values. All values larger than 999.999 are therefore defined as zero.
- By reclassifying a raster before conversion to vector format the amount of resulting objects can be reduced and the size of the vector file will be much smaller.
- By reclassifying a raster with the „Reclassify" tool in ArcGIS Spatial Analyst it is important to use the class divisions according to the ArcGIS model: For example 0-5000, 5000-10.000 etc and not 0-4.999, 5000 – 9999... Otherwise the tool will produce a large dataset that is unstable and difficult to handle.

4.4   Evaluation of the intermediate results

Evaluation of the method

The evaluation of the intermediate results was an ongoing iterative process during the whole analysis. The evaluation was mainly based on interviews and comments from local experts on surface water management – both in the planning department and the technical department (Figure 31).

The evaluation leaded to several improvements of the method, for example:

- Selection of features that were added to the height model as breaklines.

- Determination of the minimum size for the ducts that had to be lowered in the model with the open ducts.

- Additional integration of closed creeks that were not represented as pipes in the water database.

- Determination of the minimum size of the water catchment area for defining a flood stream (Chapter 4.3).

- How and where bridges and underground passages had to be lowered.

The interviews also revealed the importance of sinks and flat areas for the presentation. They give a good indication on potential problem areas.

In addition a database with a documentation of "emergency calls" concerning flood-events was evaluated. But the entries in this database were not systematically classified, so that it was in a lot of the cases not possible to distinguish whether the flooding was caused by rain or a pipe burst. The comments from local experts proved to be much more helpful.

Evaluation of the presentation

An evaluation meeting to test the user-friendliness of the map was held on the 28th of august 2013 with users from different departments. It revealed that the colours for both the flood streams and the sinks had to be changed. The originally blue colour for flood streams was difficult to distinguish from existing streams. Also the change in saturation for the different values was rated as confusing. The users also desired another colour for the green sink areas that they would associate more with danger. Therefore the colours were changed to a darker and lighter purple for the two flood stream datasets and reddish colours for the different sink depths.
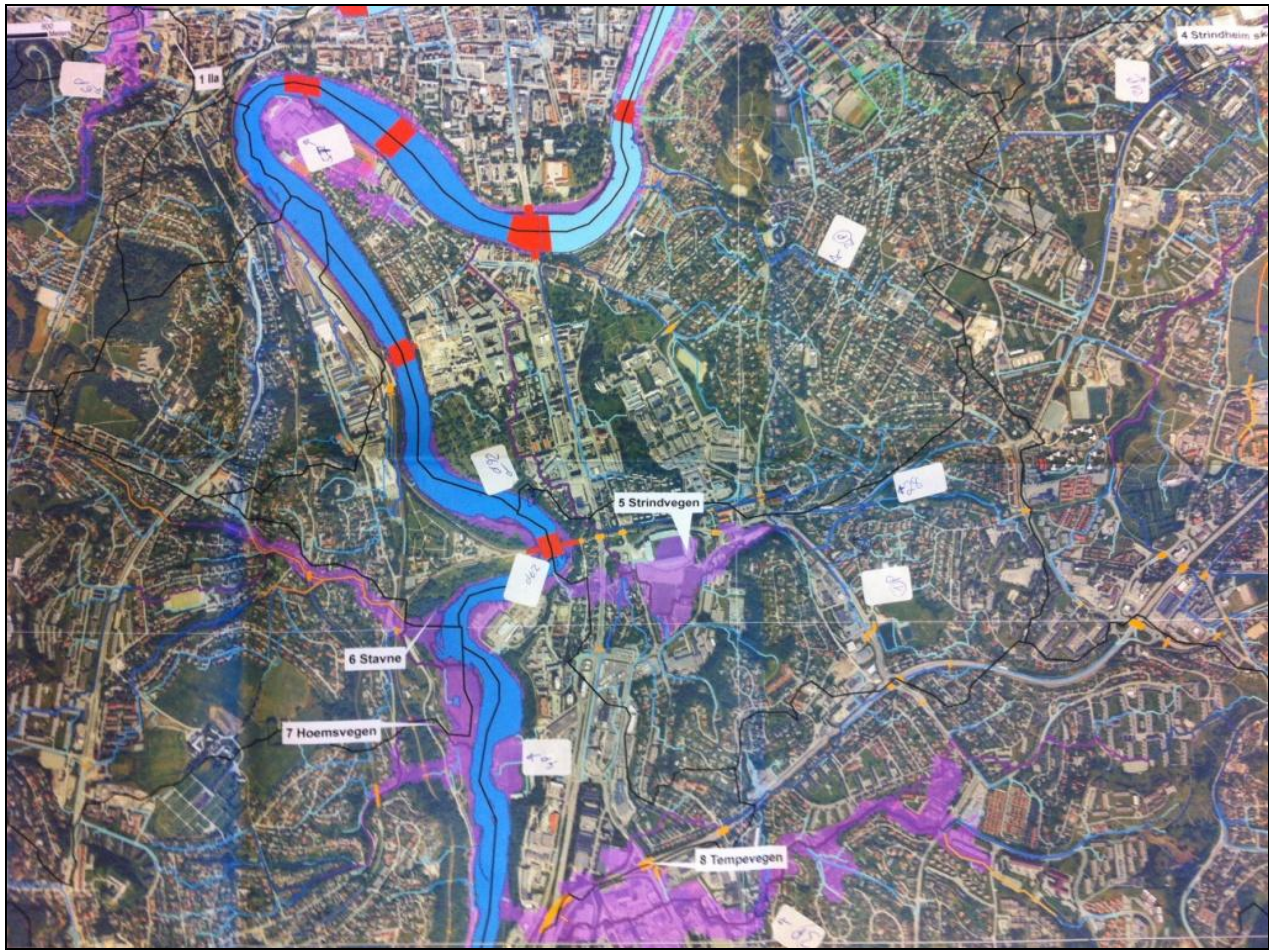
Figure 31: Printed map with markings on areas that were identified during evaluation meetings with local experts on surface water management in Trondheim.

Lessons learned:

- Local experts on the management of surface water should be involved in the process as soon as possible.

- Printed paper maps were in this project much better suited to present results and to facilitate a meeting with a few participants than a presentation on a screen. Especially people that are not used to read digital maps find it much easier to orientate on a printed map. And it makes it easier to document the comments by marking areas on the map. When the participants can self put the marks they feel "ownership" to the result and are more engaged in the discussion.

4.5   Further analysis and preparations for the presentation

Additional layers

In addition to the flood streams also sink areas, watersheds and a slope raster were calculated for the whole Trondheim and are now included in the presentation of the map. They give a coarse indication where the water is likely to accumulate.

For the definition of sink areas the difference of the filled und unfilled DEM with z values in "meter" was calculated by using the "Minus" tool in Spatial analyst. In order to determine the sink depth in centimetre the resulting distance was multiplied with 100 and afterwards converted to integer values. Sinks lower than 25cm and smaller than $3m^2$ were removed. For the presentation, the result was reclassified to four classes and converted to vector format.

Watersheds were calculated for whole Trondheim in 2011 on base of topographical vector data. A hydrological correct height model was generated with the "topo-to-raster" tool. Pour points for the creeks and rivers with all-year-round water flow were manually digitized and snapped to the flow accumulation raster with the "Snap Pour Point" tool. For the determination of the watershed areas the tool "Watershed" was used (Figure 3).

A slope raster for whole Trondheim was calculated on base of a 10x10m height model. It was constructed by bilinear resampling of a 2x2m height model that was delivered together with the laserdata. Different resolutions were evaluated (2x2m, 5x5m, 10x10m, 25x25m) for this calculation. The 10x10m resolution gave the most appropriate results for an overview over steep and flat areas in the resolutions of the different levels in the communal development plan in 1:25.000, 1:10.000 and 1:1000.

Preparations for the presentation

The reclassification of the flood stream vector data from 11 to 6 classes had resulted in a large dataset with a lot of objects. A lot of adjacent line objects fell into the same class, so that the amount of features could be reduced by applying the "Dissolve" function to single part features.

Minor flood streams from 25.000 to 50.000 will only become a problem in non-urban areas without a water drainage system (see Chapter 5.1). They are therefore presented in an individual dataset that can optionally be added to the view.

The colours for the two flood stream datasets and the sink depths will be changed according to the outcome of the evaluation described in Chapter 4.4.

On nearly flat areas like lake and river surfaces, the flood streams show unnatural patterns like straight lines or a zig-zag-pattern. This is both confusing and disturbing for the users of the map. Therefore a polygon for water bodies was added as a covering top layer to the map.

Publication of the data in the communal map application

The flood streams are presented in the communal map application in form of a caution map together with other data on sea level rising (TM 2013в).

Accompanying to the published map guidelines for the use and interpretation and were developed and published on the communal internet pages in Norwegian (TM 2013c).
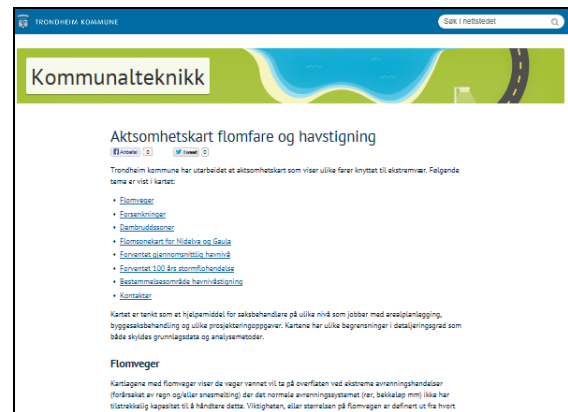

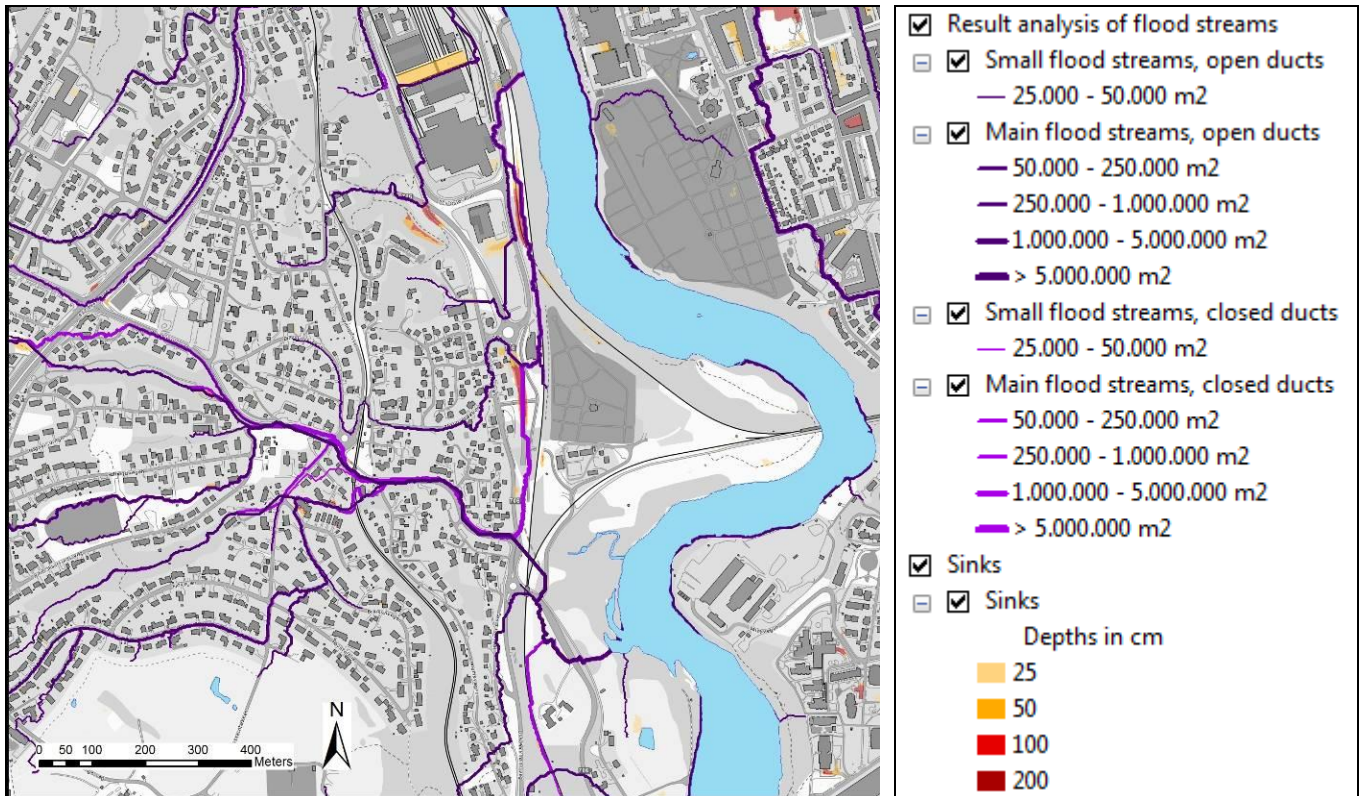**Figure 32:** Screenshot of the communal internet page on guidelines for the map (TM 2013c)

Figure 33: Detail of the caution map on flood streams with the new colours following the recommendations of the user evaluation described in Chapter 5.4
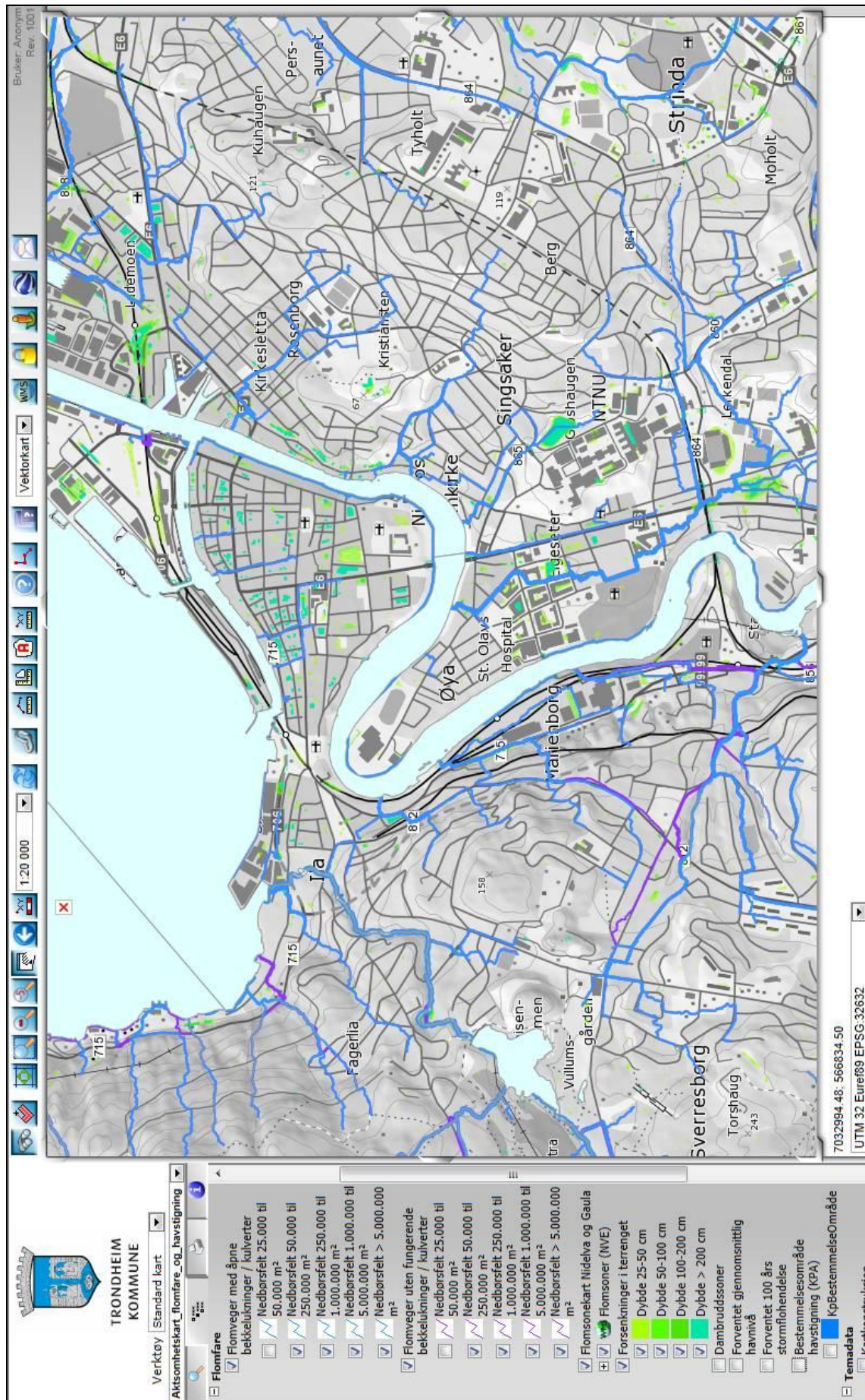
Figure 34: Screenshot of the caution map on flood streams published in the Map application of Trondheim (TM 2013B). On the 22nd of October 2013 the map showed still the old colour-scheme.

5   Final assessment and results

5.1   Field assessment

On the third of January 2013 the conditions were perfect to conduct a field assessment. The ground was still frozen and covered with snow and ice which partly melted during the daytime after some days with temperatures around °C. A heavy rainfall (5mm per hour and m^2) was predicted in the weather forecast for the first part of the day so that I and my colleague Birgitte Johannessen could prepare for an assessment tour around the inner, mostly urban parts of the city. She drove the car while I was sitting in the front-seat with a printout of the map on my knees. While driving, I "predicted" the occurrence of flood streams we should pass according to the map. A rightly predicted flood stream was rated as a "right" point (case 1). (I guess we were the only people in town happy to see the flooding on the streets...) In total 78 places were observed and documented under the field assessment (Table 3 and Figure 38).

When a flood stream on the map did not show up on the street (case 2), we distinguished two cases:

> 2a) The flood stream was led under the street in a duct or underground passage– this was accounted for as "right".

> 2b) We couldn`t recognize a duct or underground passage. This was accounted for as "partly wrong", because we weren`t sure if maybe the amount of rainfall was not enough on this day for the flood stream to evolve.

In 11 places we noticed flood streams on the street that weren`t indicated on the map (case 3). In this case we distinguished two cases that both were rated as "wrong"

> 3a) We could identify a flat area above from which several flood streams evolved, while the calculated flood stream just flowed into one direction.
> 3b) We couldn`t identify a reason.

Table 3: Cases and results of the field assessment

Cases	Rating	Symbol	Amount	Percent
1) Flood streams on the street that were also predicted on the map	right		46	52%
2a) Flood streams on the map that did not show on the street because of a duct or underground passage.	right		17	19%
2b) Flood streams on the map that did not show on the street without a duct that we could recognize	partly wrong		15	17%
3a) Flood streams on the street that did not show on the map because of a one-directional flow from flat upper areas in the analysis.	wrong		8	9%
3b) Flood streams on the street that did not show on the map, without a recognizable reason.	wrong		3	3%

5.2   Results

The **final output** of this project includes:

- Two vector polyline datasets for the flood streams in two scenarios: Open and closed major ducts and underground passages. The values of the line objects indicate the size of the water catchment area in m^2. The only exceptions are flood streams close to the eastern and southern communal border, where the water basins exceed the extent of the analysed area.

- A polygon dataset for the depression areas (sinks) with an indication of their depths in centimetre.

- A slope raster with a resolution of 10m x 10m.

- A documentation of the method in form of an internal "recipe book" written in Norwegian and a set of ArcGIS toolboxes.

Accuracy according to the field assessment

With a right prediction of 71% of the observed spaces and only 12% clearly wrong predictions, according to the field assessment, we are quite satisfied with the accuracy of the map. Earlier documented flood events also proved that the calculated flood streams especially in combination with the sink areas give a good indication were problems might evolve (see title picture on the envelope and Figure 35).

In 11 cases the observed flood streams on the street did not show on the map. In 8 of these cases this can be explained by the D8-algorithm of the flow-direction tool in ArcGIS, that only allows for a flow in one direction. Here the analysis can be improved by using another algorithm – see discussion in the Chapter 3.3 and 6.2.

Deviation between the two scenarios "open" and "closed" ducts

The simulation of all ducts closed showed as expected some deviation in the prediction of flood streams compared to the scenario where the major ducts are open (see Figure 36). These deviations concern usually small distances of a few hundred meters where the flood stream proceeds on the road instead of passing under in the duct. During the assessment this effect was only observed in one case. And it is unknown if the flood water also passed the duct, so that both scenarios might be correct for this situation.

Other deviations between the two simulations seemed to be caused by a randomly distribution of the flow direction on flat areas, where the likelihood for two or more directions is the same (Figure 37).

Figure 35: Detail of caution map for flood streams indicating a risk for a building and a picture of a flood stream running through the building on the 22nd of September 2004. (AFTENPOSTEN 2004)
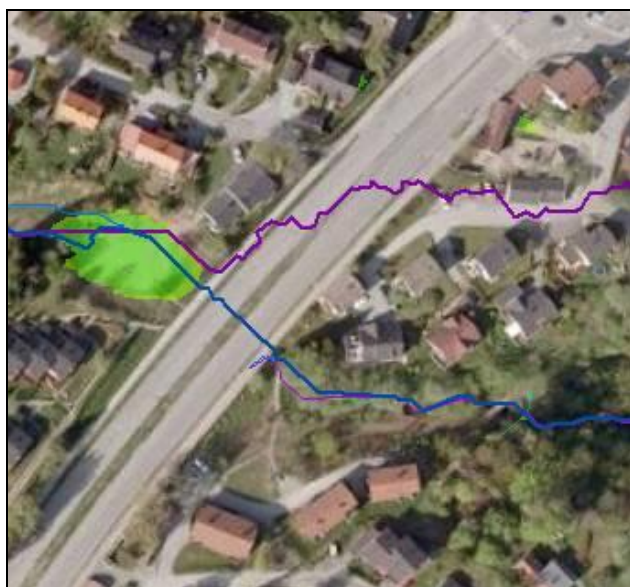

Figure 36: Difference between the flood streams for open ducts (blue) and closed ducts (purple) caused by the lowering of a duct crossing the street in the height model.
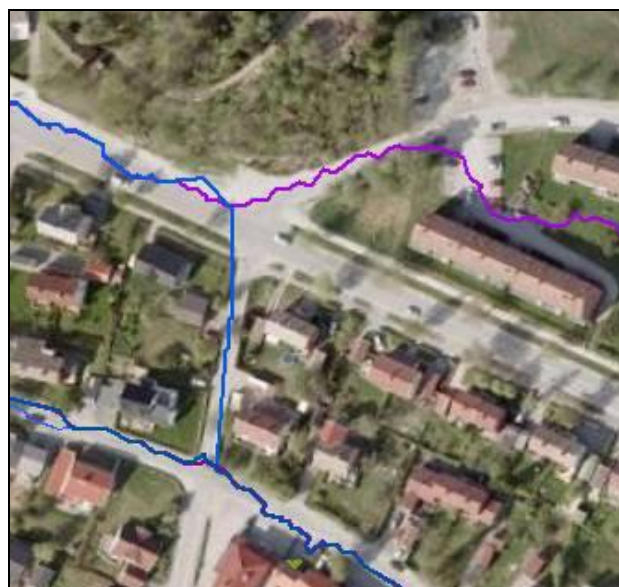
Figure 37: Difference between the flood streams for open ducts (blue) and closed ducts (purple) most likely caused by a random flow effect from a flat area.
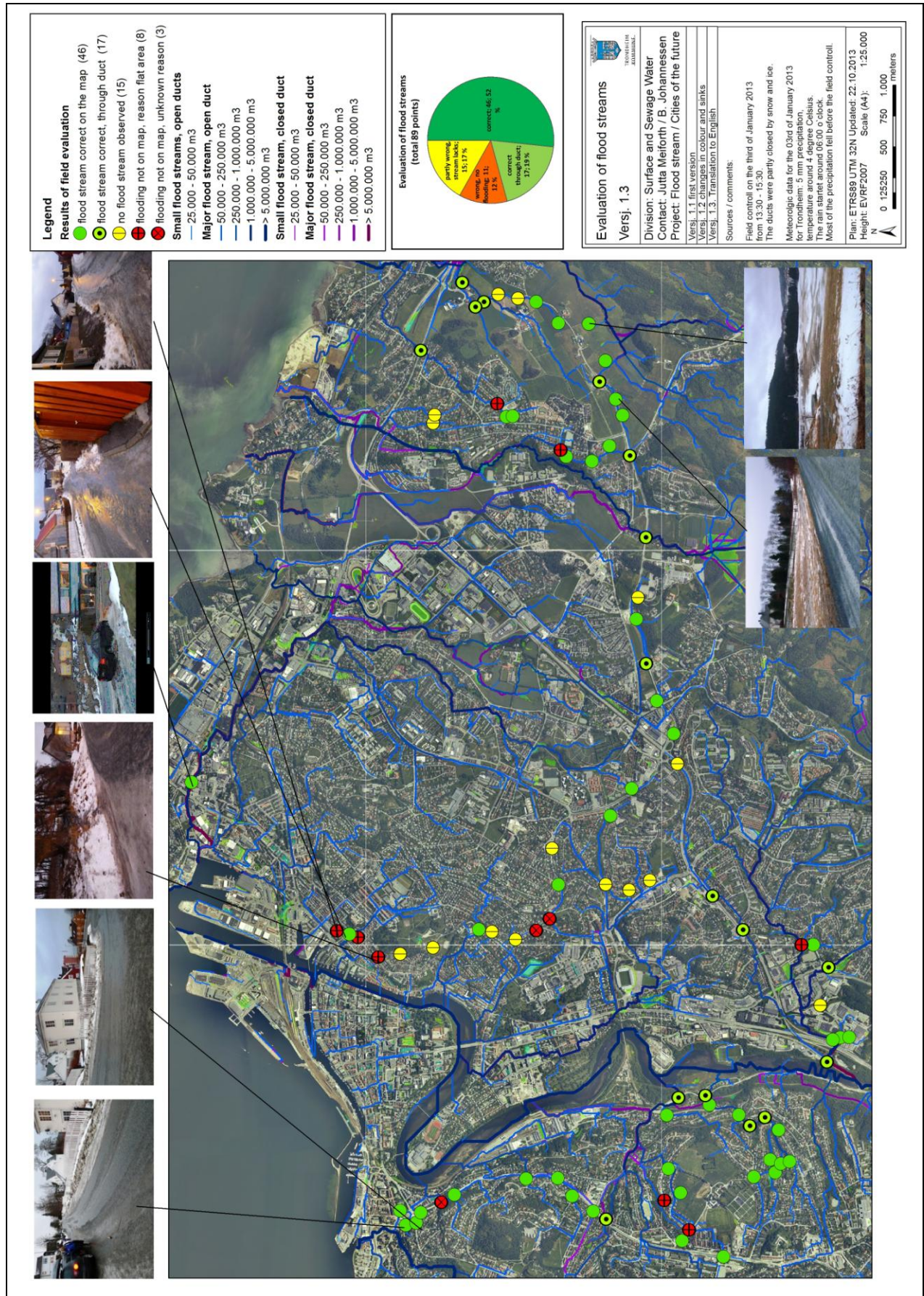
Figure 38: Map showing the results of the field evaluation and some pictures taken on the tour

6   Discussion and prospects

6.1   Conclusion

The overall conclusion of this project is that the method used in this project to determine flood streams in Trondheim is suited to meet the objectives and the requirements described in Chapter 5 for the use of flood streams in communal planning.

The hydrology tools in ArcGIS Spatial analysis proved to be easy to use, to be well suited for documentation and to give an overall satisfying result. But these tools also have some restrictions that both lowered the accuracy and constrict the use of the results. Considerations how these restrictions can be overcome in an update or further development of the map are discussed below.

While the implementation of the "core" hydrological tools in ArcGIS was strait forward, the main challenge and most time consuming step of the analysis was the building of a hydrological correct height model, especially the acquisition and preparation of the data.

An essential aspect for the success of this project was the close collaboration with the local experts on surface water management.

6.2   Possibilities for improvement of the method

In this section comparatively simple changes of the used method are described that can easily be implemented in an update of the map.

Simplifying the method with a better data source

With a better data source the process could be simplified and the accuracy of the height model could be increased. Requirements on the lidar data would be a more dense acquisition of data with at least 5 or 10point/m^2. This would give the possibility to create a height model with a higher resolution that also catches the edges of sidewalks so that these eventually don`t need to be modelled as breaklines. In addition, the data should be properly classified, so that ground points, vegetation, buildings, bridges and water can be clearly identified and can be used directly in the model.

2D algorithm for the flow direction

The field assessment (Chapter 5.1) revealed that the restrictions of the one dimensional D8 algorithm in the flow direction tool of ArcGIS are a major cause for inaccuracy in this analysis, especially on flat areas where flood streams divide. This restriction can be overcome by using 2D algorithms that allow for a runoff in multiple directions, like the Multiple-Flow algorithm or the D-infinity algorithm that were presented in Chapter 3.3.

If ArcGIS is not extending its flow direction tool, the following open source software can be considered: The open source software SAGA GIS provides a choice of different flow direction algorithms including the Multiple Flow Algorithm (SAGA USER GROUP ASSOCIATION 2013). The D-infinity algorithm is used both in the r.flow tool of the open source software GRASS (GRASS DEVELOPMENT TEAM 2011) and the TauDEM hydrology tools which can easily be integrated in ArcGIS as a standard ArcGIS toolbox (TARBOTON 2013).

Simulation of changes in runoff through the accumulation of snow

Snow and ice often forms a smooth crossover on sidewalks so that the flooding water needs lesser energy to cross these barriers. This effect occur irregular, both in time and space. It can be presented as a new scenario with a lower likelihood by omitting the breaklines for the pedestrians in the analysis.

Improvement of the evaluation and assessment

Field assessments as described in Chapter 5 should be carried out to different times of the year to cover different amounts of precipitation and a variety of conditions concerning the distribution of ice and snow.

In order to cover a broader range of weather conditions the use of data from insurances is now under investigation. Trondheim takes part in a nationwide project to evaluate the use of this data for the analysis of risks caused by flooding and other natural hazards (VESTLANDSFORSKNING 2013).

6.3   Advanced development of the method

In this chapter some considerations for a further development of the method are presented. They will answer additional questions that exceed the objective of this project.

Calculating the total amount of surface water

Given the size of water catchment area for each object in the flood stream, the total amount of surface water for each object can easily be calculated when the amount of precipitation per area unit (here 1 m^2) is known.

By calculating total amounts of water the watershed areas outside the communal boundary need to be taken into consideration. The nationwide height model in a resolution of 10x10m in combination with topographical vector data can be used to derive a flow accumulation for these areas.

In situation with none-frozen ground the different land cover types hold back surface water to different amounts, leading to differences in the run-off factors. Bogs are for example very efficient water accumulators and they occur numerously in the forests of Trondheim. A weighted overlay raster for the flow accumulation analysis could be used to simulate different runoff characteristics for land cover types defined by the Norwegian Area Resource Map AR5 in scale 1:5000 (SL 2012)

Another result of the field work assessment described in Chapter 5 was that the water pipe system under the streets still leads away a considerable amount of runoff water, in spite of the snowy conditions during field work. The assumption of 100% runoff (weight factor 1) was therefore not appropriate for the whole area on this day, even under winter conditions with frozen ground. This effect could be taken into account by applying a weight factor for the surface runoff that is lower in urban areas with a drainage pipe system than in natural or rural areas without a drainage pipe system.

The varied relief in Trondheim causes a heterogeneous distribution of precipitation in the municipality. This fact can also be taken into account in the weight layer. A raster layer with mean amounts of precipitation can be obtained by the Norwegian Meteorological Institute (NMI 2013).

Modelling a chronological process of the water accumulation

While the flood streams of this project are only allocated one static value for the size of the catchment area, the potential risk of flooding events are in reality highly dependent on the chronological process of the water accumulation. A simulation of a chronological water accumulation requires the building of a stream network. In ArcGIS Spatial analysis (ESRI 2012e) the Hydrology tools "Stream order", "Stream line" and "Stream link" allow the building of such a stream network.

An indication of the time factor in the water flow can be simulated with the "Flow Lengths" tool in ArcGIS. It creates a raster that shows for each cell the longest upstream or downstream distance along a flow path. The measure for the upstream option can be used to calculate the time spans that correspond with the concentration of flow channels in a basin. The analysis can be further refined by adding a "cost" factor according for example to the slope. Basic introduction in this topic is provided amongst others by TARBOTON ET.AL. 1991, GREENLEE 1987, MARK 1988, GARBRECHT & MARTZ 2000.

Modelling the dispersion of surface water in space

Another restriction of the method used in this project is the fact that the resulting line features don`t show a dispersion of the flooding water in the terrain. A method to determine areas prone to flooding in Trondheim should take into account the high variations in both terrain and flood levels. It should also not be too complex, so that it can easily be applied for the whole communal area.

Regular floodplain analysis is based on detailed hydraulic analysis using measured cross sections and overlaying the calculated floodplain with a digital terrain model (DTM). This approach is not suited for the whole area of Trondheim because it is very complex and requires a lot of measured and individual input data for each stream. Other methods that use standard river profiles as developed for Finland (MIKKO & MIKKO 2008) or fixed water level rise as simulated for Ireland (ADAMSON 2008) are also not suited to the situation in Trondheim, because they are too standardized and don`t account for the local variations in both terrain and flood levels.

A coarse indication of the dispersion of flood water in the terrain can be given by calculating a variable buffer zone around the flood streams. The buffer zone varies in width depending on the size of catchment area and the steepness of the terrain. In areas with sinks this buffer will be expanded.

The Norwegian Water Resources and Energy Directorate (NVE) developed and tested a method for the determination of areas prone to flooding without the use of detailed hydrological or hydraulic calculations (KRISTENSEN & PEEREBOOM 2008). In this approach, the flood extent was derived from a DTM based on a hydrological analysis of the expected rise in flood level at a given location along a river. Instead of real measured profiles, approximated cross sections are constructed automatically with a virtual DTM that is based on buffers around the flood streams. The "virtual" cross sections are derived as a set of narrow strokes through applying a watershed analysis for all individual river grid cells as pour points. These strokes can then be given the maximum rise of water level derived from the virtual DTM, which gives a calculated flood level for the stroke. By comparing this height with the height in the original terrain model the floodplain can be extracted.

6.4   Application of the results and prospects

Risk analysis for buildings and infrastructure
By applying a buffer analysis to the determined flood streams and sinks it is possible to define existing buildings lying on or close to areas that are prone to flooding. This analysis is planned for official buildings in Trondheim like hospitals, schools, kindergartens and buildings with values in cellar rooms like archives of museum and laboratories.

Indication for the need of upgrades of the drainage pipe system
A comparison of the existing drainage pipes for surface water and the analysed flood streams will give evidence for the need of new pipe systems or a readjustment of their size.

Identify high risk areas for avalanches
In Trondheim large parts of the slopes are formed by clay and sediments. In combination with the varied temperatures and high precipitation this leads to a partly high risk of avalanches. It is planned to use the results of this project for the identification of high risk areas for avalanches caused by layers of soil that are saturated with water and glide over more dense, impermeable soil layers. In this analysis the proximity to flood streams will be an important factor.

Regulations on flood streams in communal planning
The results of this analysis are integrated in the communal development plan in Trondheim as a caution map (Chapter 5.2). New regulations following the development plan (TM 2013B: 15) state, that in areas with flood streams and sinks special requirements for the new construction of buildings need to be undertaken. They include special adaption in reference to for example the placement of buildings, the molding of the terrain and the planning of entrances for the basement and cellar. Also further investigations on the actual risk caused by flood events need to be undertaken. In areas with indication of heavy flood events the construction of new buildings can also totally be forbidden.

There is still a high amount of insecurity in the administration how to interpret the flood streams and which precautions are suitable and can be demanded from the constructor. Another aspect in this context is the question of responsibility. Who pays for damages caused by flood events that occur on construction sites that were approved by the municipality? The need for clear guidelines both on regulations but also on the method is obvious and is currently discussed with the Norwegian Water Resources and Energy Directorate (NVE).

Development of a method for whole Norway

Trondheim takes part in a working group that evaluates methods to analyse flood streams. The working group consists of GIS analysts and water experts of some municipalities, the Norwegian Water Resources and Energy Directorate (NVE) and consulting companies. The objective is to develop a guideline that should help municipalities to implement these methods by themselves and to give recommendations for a nationwide map on flood streams.

The experiences in Trondheim showed that the accuracy of the result strongly depends on the quality of the used height model and the algorithms. With reference to the juridical consequences of a flood stream map in communal development planning, the need for a standard method based on uniform data for whole Norway became evident. This issue is currently discussed with NVE that is already working on a nationwide "flood susceptibility map" with a coarse resolution (NME 2013).

Considering the prospects for rising precipitation in combination with both higher and more unstable temperatures the modelling of flood streams will become even more important in future. The ongoing improvement of both hydrological tools and available datasets in Norway like the acquisition of laserdata but also the mapping of urban pipe systems is offering exciting future possibilities for hydrological analysis in urban areas in Norway.

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8   Indices

8.1   Figures

8.2   Tables

9   Epilogue

After talking so much about rain and snow – the combination is called "sludd" in Norwegian – I would like to invite you to the beautiful and sunny sites of Trondheim...

... its old wooden houses with small charming cafes,
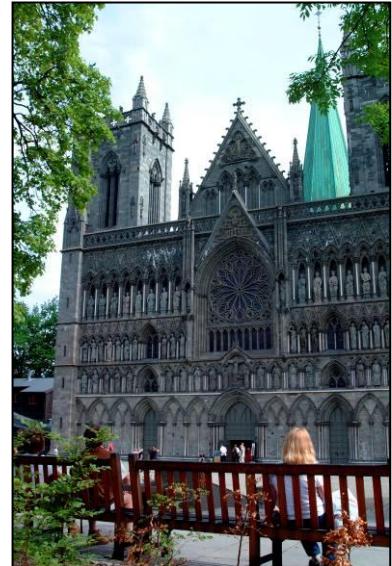
... the ancient Nidaros Dome – the world's largest northerly gothic cathedral,

... a stroll along the beautiful sides of the river "Nidelva", with salmon, beaver and otter right in the town centre,

... and last not least the beautiful bays at the Trondheim fjord, ideal for a barbecue in summer with the midsummer sun during the night. And in the winter months, when you are lucky, blue-yellow wafting curtains of northern light create a magical atmosphere.

Feel welcome!

And however the weather might be on your trip to Norway – remember the Norwegian wisdom: "Ut på tur - aldri sur!"   (Pictures: TM 2013E)