Identification of areas exposed to flooding in Norway at a national level

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ABSTRACT

NVE is the responsible public authority concerning river related hazards. NVE has published guidelines on how municipalities should consider river related hazards in their spatial planning. The guidelines stipulate municipalities should further assess the danger of flood in areas that may be food prone. In order to assist the municipalities NVE has committed itself to mapping map these continuance areas.

A similar product is required from the EU flood directive. The EU flood directive stipulates the assessment of flood risk by performing a small scale analysis to determine where to do more detailed mapping.

To methods for mapping of areas prone to flooding at a national level were developed. One method based on geomorphology and one based on hydrology. Both methods are described in this paper. Comparing the advantages and disadvantages of both methods, the hydrologic method is considered to give the best results in the Norwegian situation, considering the availability and quality of the input data.

Keywords: flooding, areas at risk for flooding, GIS analysis, EU flood directive

INTRODUCTION

Background

Norway is a country with both terrain and weather conditions that produces floods on a regular basis. Its northern position makes for long winters with low runoff and snow accumulating in the mountains, leading to high runoff in spring resulting in a regime with the highest floods during spring .In the western coastal area autumn and winter floods dominate. In this region the climate is milder due to influence of the ocean and the catchments are generally small leading to short runoff times. Although sparsely populated, most urban activity is concentrated along the valley floors. Good farmland was found on the flood plains and formed the basis for early settlement. Further development and infrastructure such as roads and railways consequently follow the valley floor, and are thus subject to flooding.

The traditional approach to floods was dominated by physical flood protection works such as levees and erosion protection consisting of stone rip rap. After the damaging flood in 1995 it was clear that this traditional approach towards floods did no longer hold. In the aftermath of the flood the Commission on Flood Protection Measures was established by Royal Decree. The Commission produced an Official Norwegian Report (NOU 1996:16) and the report was followed up by a governmental White Paper (nr 42 1996-1997 – Measures against floods). A new integrated approach in flood management was proposed based on the idea that the *'most important measure to reduce flood damage in the future is to improve land use planning in flood prone areas*'. This White Paper is regarded as a national action plan for Norway on measures against floods.

Flood Risk Management

The national Planning and Building Act states that local municipalities are responsible for taking natural hazards into account in land use planning, and could be liable if damage occurs. The planning process in a municipality is typically split into three levels:
Municipal plan - giving principal strategies for land use within the municipality,
Zoning plans - where specific areas are zoned for different land use with detailed regulations
Building case - where the processing of building application is done.

The national Planning and Building Act further states that development is not allowed, unless safety is at an "***acceptable level".***

The Norwegian Water and Energy Directorate, NVE resides under the Ministry of Petroleum and Energy with responsibility for the management of the nation's water and energy resources. NVE plays many roles in relation to flood risk management. NVE provides advice to the municipalities, but according to the Planning and Building Act, NVE may also object to land use plans if national interests or regulations are not followed. The Ministry of Environment has the final say if agreement is not reached between a municipality and NVE.
In its role as adviser to the municipalities NVE has developed a national guideline defining the acceptable safety levels with respect to floods and other hazards related to rivers. The guideline defines and quantifies the acceptable hazard levels for different types of assets.
To further support the municipalities the flood mapping project was started in 1998 where NVE has made detailed flood inundation maps for about 120 river stretches. These flood inundation maps have contributed to the awareness of and communication with NVE concerning flood risk. The maps are also used in case of contingency planning.

Though the guideline did clarify to local authorities what were acceptable levels of risk for different assets, it did not capture planning objectives according to the Planning and Building Act. Furthermore there was a need for more clarification as to how the guideline could be implemented in land use planning processes. This has led to a revision of the guideline 2007 /3/. With the revision of the guideline the emphasis has shifted form solely flood hazard to include landslides, but ultimately describing procedures applicable to all natural hazards, giving advice as how to proceed with land use planning in areas with a potential risk. A stepwise procedure for assessing the hazards has been designed to fit with these levels. The following procedure is now recommended:

Municipal plan:	potential hazard should be identified
Zoning plan:	the actual hazard should be described and risk quantified
Building case:	a satisfactory level of safety must be documented

This procedure ensures that areas with a potential hazard are identified at an early stage and asks for hazard and risk mapping differentiated for each level. A lot of areas with high flood risk are covered by detailed flood inundation maps from NVE, but there is no national overview of potential hazard areas. There is a risk that the lack of overview leads to new development in unmapped, but still flood prone areas.

Small Scale National Flood Risk Mapping

To help municipalities identifying potential hazard for flooding it was decided to undertake a small scale national flood risk mapping. This mapping will provide an overview very much in line with the first step of implementing the EU flood Directive – the Preliminary Flood Risk Assessment /4/.

The aim is to develop a cost effective method based on available datasets and knowledge which is easy to understand for both municipalities and the public.

Although there is a lot of experience in detailed floodplain mapping in Norway, doing a national small scale flood mapping covering the whole country of Norway provides us with a whole new set of challenges.
Norway is a big country when different water related phenomena are to be mapped at a national scale. The total area of Norway is 324,220 km² and consists of a vast amount of rivers and lakes:

Lakes: - Total number 968444, approx. 250 000 > 2500m^2
- Covers 17869 km^2
Rivers: - Approx. 410 000 km of rivers and streams

Available Data

Rivers – river network

NVE has established a national river network derived from base map data in scale 1:50000. In the river network all rivers, streams and lakes are interconnected and are identified by a number. A network gives opportunities to perform upstream and downstream analysis, which is impossible when rivers are represented as lines and polygons. Furthermore have all river reaches in the network been classified according to Strahler river order.

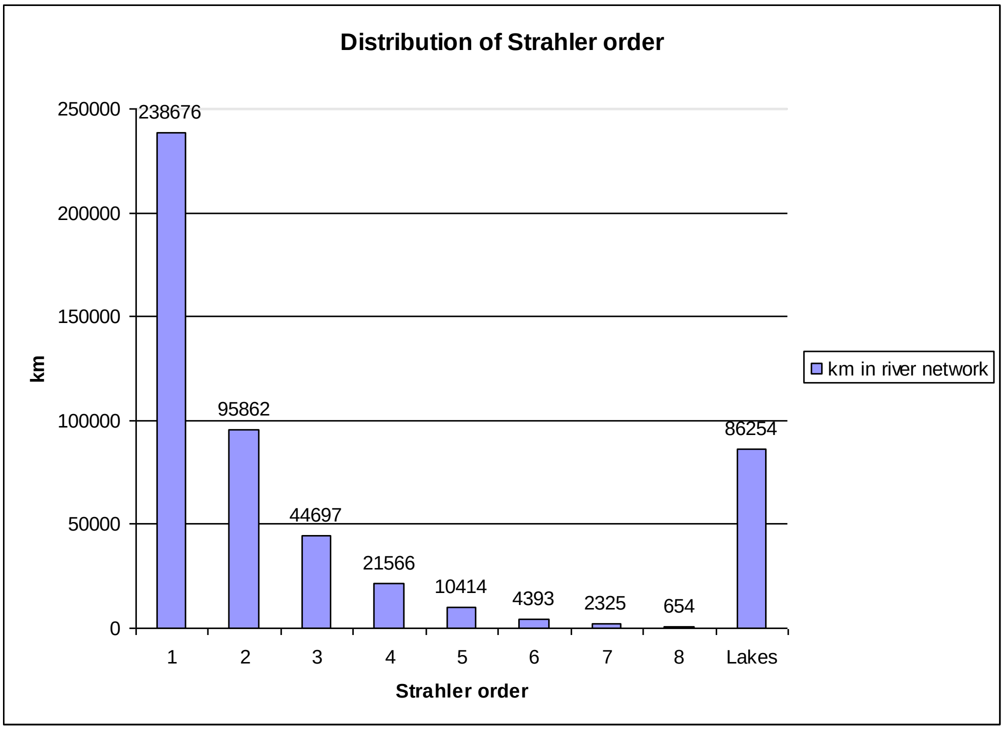


Figure 1: Distribution of rivers according to Strahler order

Elevation, Digital Terrain Model (DTM)

When mapping of areas prone to flooding is performed at a national level there is a limitation in the availability of accurate base map data. Several sources are available for information about elevation, but only one DTM is available with national coverage. Together with the fact that the mapping should be cost effective it was decided at an early stage that the national 25x25m digital terrain model (DTM) from the Norwegian Mapping Authorities should be the preferred source for information about elevation /5/.

The Norwegian Mapping Authorities have developed a national DTM with a spatial resolution of 25 x 25m. The DTM is made from contours with 10m and 20m equidistance from base maps in scale 1:50000. Approximately 60 % of the country has contours with 5m equidistance. More detailed elevation data are available along some of the main roads and in urban areas. The national DTM has it limitations in terms of accuracy. The standard deviation is between 4 and 6m although in study areas much better results were found with standard deviation between 2.7 and 4.4m /5/.

Hydrological data

NVE has a network which consists of 600 gauging stations. The measurements are kept in NVE’s hydrological database HYDRA 2.

METHODOLOGY

Introduction

The main focus has been to investigate the possibility to derive areas prone to flooding based on our national DTM. Methods used for small scale flood assessment in other countries such as Finland and Ireland were studied.
The Irish method uses a fixed water level rise (1m) that is superposed on the high of the river bank taken from the terrain model at cross sections. The intersection of the flood level with the terrain to get the extent of the flood plane is also derived at the cross sections. These are then used to interpolate extent of the flood plane /2/. Because of the variations in both terrain and flood levels this method is but not applicable in Norway.
In Finland flood levels are calculated using Bernoulli's and Manning's equations with standard river profiles. The water levels are then extrapolated using an advanced GIS method based on cost allocation /1/.
Because of the variations in the Norwegian terrain, standard river profiles in Bernoulli's and Manning's equations can not be applied. Extending the flood plane with the advanced cost allocation method is time very consuming for the vast amount of rivers in Norway. That in combination with the inaccuracy of the digital elevation model makes also this method not well suited for the Norwegian situation.

Two different approaches have been evaluated:

A) Geormorphological, slope analysis and use of the river network

B) Hydrological ,deriving the flood extent from the DTM based on a hydrological analysis of expected rise in flood level at a given location along a river reach

Common for the different approaches is the use of the 25 x 25m DTM.
The main challenge is the coarse resolution of the DTM. Another challenge is to develop a product which is recognisable for the public and easy to communicate to the local authorities and the public.

A) Geomorphology, slope analysis and river network

The main hypothesis in this approach is that flat areas in the vicinity of rivers were created in a process of sedimentation and thus prone to flooding. Flat areas can be identified by the use of a dataset representing slope. A national dataset representing slope has been calculated based on the DTM. Slope calculation is a predefined tool in most GIS software. In order the find a representative threshold value for slope, representing flat areas, the slope dataset were compared with the flood extent from our existing detailed flood inundation maps. Based on the comparative study between flood inundation maps and the slope dataset, a representative threshold value ≤ 3 degrees were chosen. Based on the threshold value of 3 degrees, all areas in the slope dataset ≤ 3 degrees were identified as flat areas or prone to flooding.

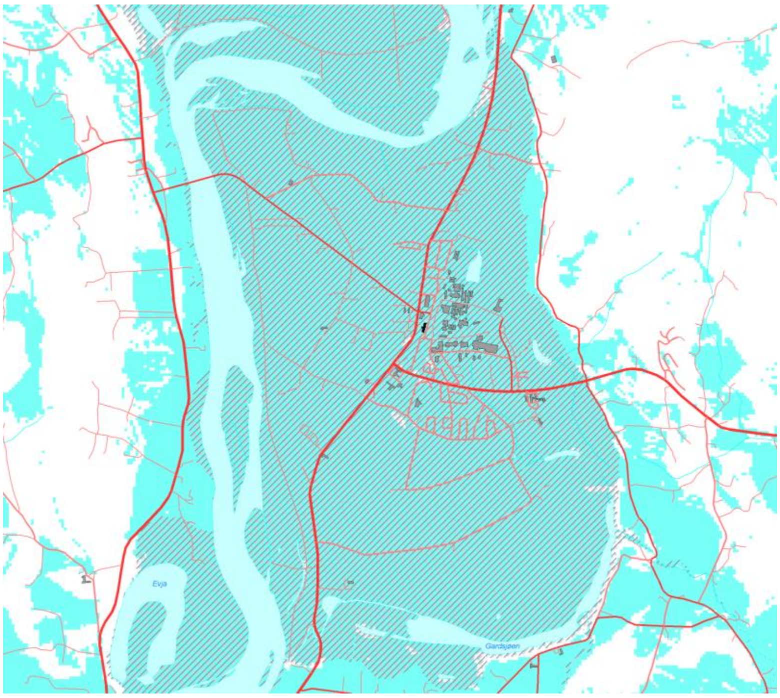


Fig 2: Extent of calculated 500-year flood (shaded area) with areas prone to flooding based on slope only

In order to reduce the extent of flat areas, flat areas that were not interconnected with the river were identified and removed. As it appears in fig.2, there is a very good correlation between the calculated 500-year flood and the identified areas prone to flooding based on this approach. The result of this simplification makes the final product much easier to read. Fig.3 and fig.4 shows the results from two other locations.

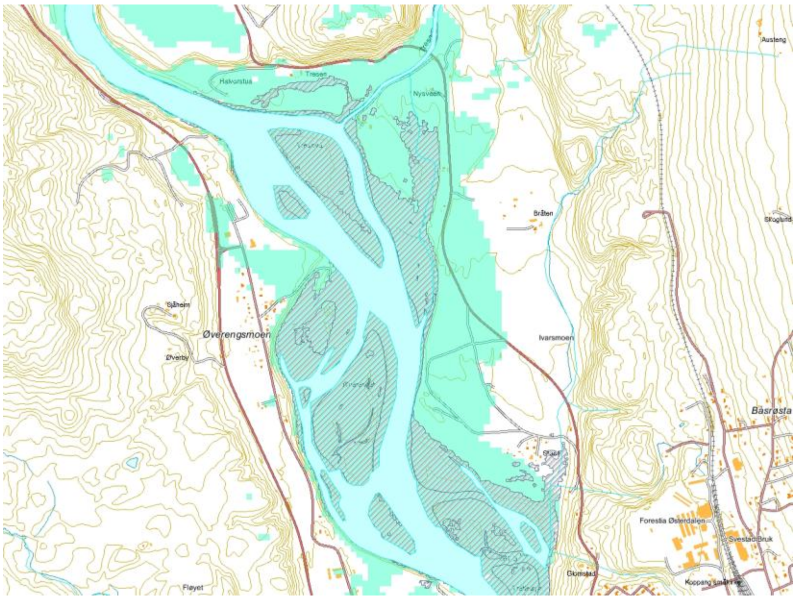


Fig 3: The figure shows the extent of the calculated 500-year flood (shaded area) at Koppang from our flood inundation maps together with the areas which are identified as prone to flooding based on slope

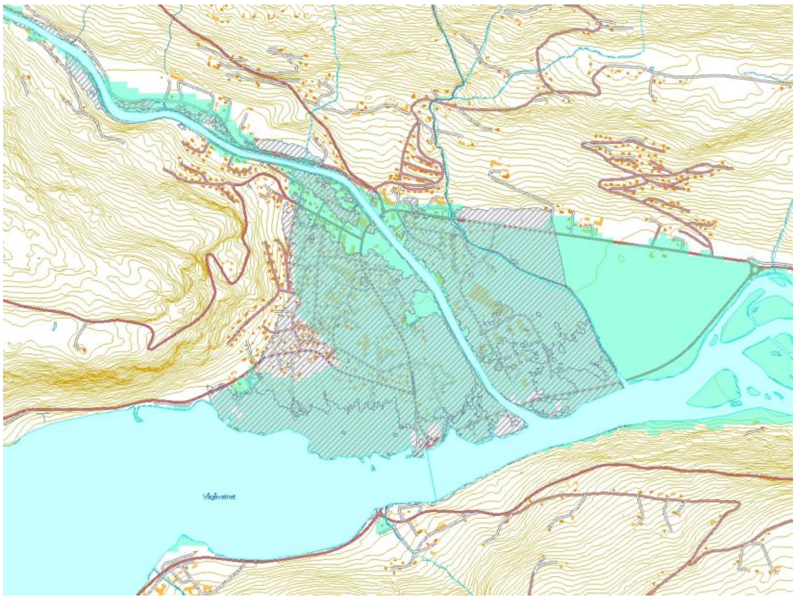


Fig 4: The figure shows the extent of the calculated 500-year flood (shaded area) at Vågåmo from our flood inundation maps together with the areas which are identified as prone to flooding based on slope

Geomorphology - Discussion

The results from the geomorphologic method show that this method works well in isolated cases. In complex river systems with lots of small tributaries reaching far up in the catchment, the method of distinguishing between flood planes and other flat areas does no longer work. This results in an overestimation of potential flood areas, especially in upstream areas close to the water divide. Norway has many of these small upstream rivers and brooks as is shown clearly in the distribution of rivers according to Strahler order in fig 1.

Underestimations of the extent of the potential flood plane occur in areas where the flood water level is really high and the water in reality reaches areas that are less than the 3 degree threshold that was use in this method.

B) Hydrology

Introduction

The basic idea was to first develop a simple method to calculate the potential maximum rise of water levels in various kinds of rivers. Then use these maximum water level rises to determine the flood water level and interpolating these to a flood plane. Combining this flood plane with the Digital Terrain Model (DTM) makes it possible to find the potentially inundated areas.

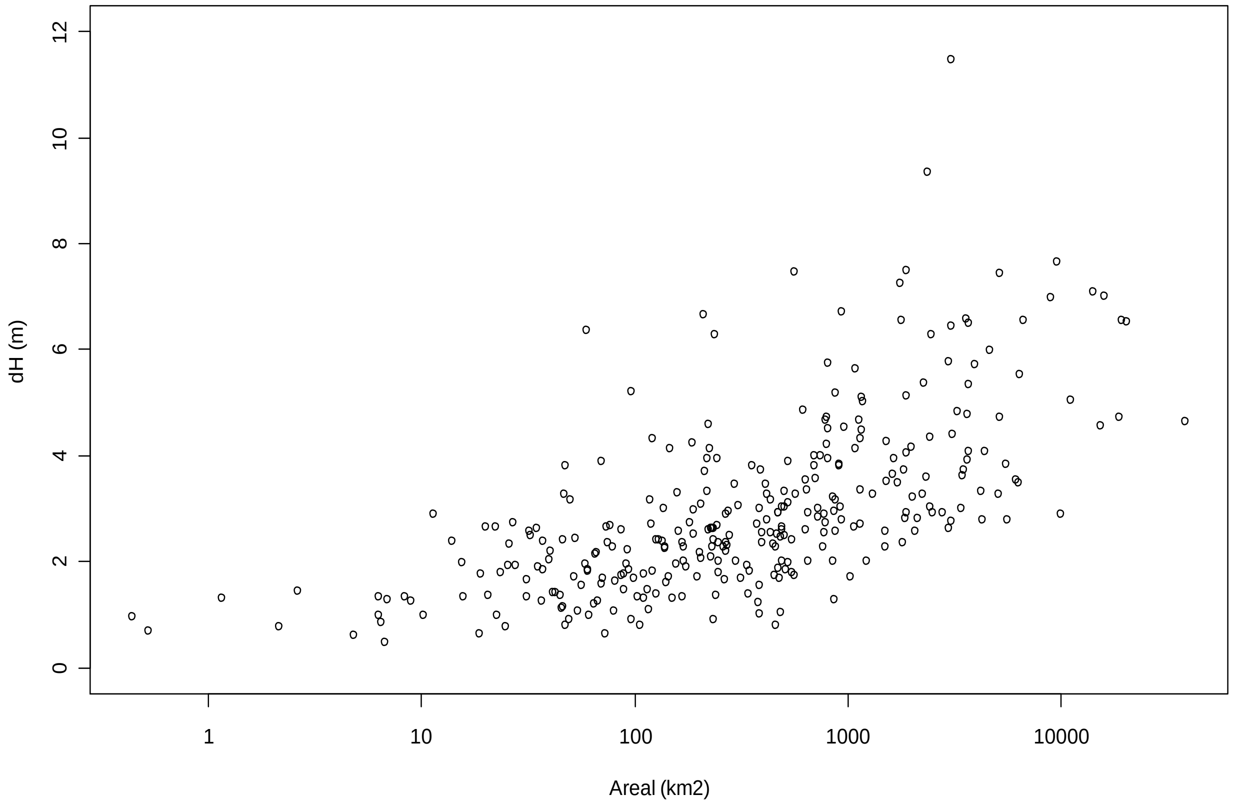
Hydrology - deriving maximum rise of water levels

The method is based on the assumption that the water level can be derived without the use of detailed hydrological or hydraulic calculations.
4 different approaches were used depending on the availability of data.

- Data from gauging stations (discharge, waterlevels)
- Catchment characteristics (catchment area, lake percentage, specific runoff)
- Catchment area
- Comparable rivers in the same area.

For approx. 150 river stretches in Norway hydraulic calculations have been made to produce detailed flood inundation maps. The rise of water levels from these rivers was correlated with discharge and catchment characteristics.

For gauging stations outside of the flood inundation map areas, rise in water level can be established based on flood frequency analysis and the discharge rating curve.



In ungauged river basins, catchment characteristics were used to estimate the rise in water level. A precondition was to use relative simple parameters that can be used for different kind of rivers, both small and big, steep and flat, different Strahler etc. Regression analyses were done with rise in water level for a 500 year flood, both at gauging stations and river stretches with flood inundation maps. The results show a moderate relation with a R2 value between 0,3 and 0,5. The regression residual is between 2 and 4 m, depending on catchment area. About the same values were found when using the rise in water level from both gauging stations and flood inundation maps. In ungauged catchments, using only area gives a slightly worse result.

The regression equations from the different approaches are listed here:

<u>Area</u>

0-1 km2:	**dH(m) = 2**
1-500 km2:	**dH(m) = 0,965 ln(Area) + 2**
>500 km2:	**dH(m) = 8**

0-1 km2:	**dH(m) = 2,83 + 0,00027 * Area + 0,0009 * Runoff – 0,15 Lake%**
1-500 km2:	**dH(m) = 2,83 + 0,00027 * Area + 0,0009 * Runoff – 0,15 Lake% + 0,64 ln(Area)**
>500 km2:	**dH(m) = 6,83 + 0,00027 * Area + 0,0009 * Runoff – 0,15 Lake%**

Hydrology – interpolating a flood plane

Using these equations a water level rise can be calculated. The catchment area is calculated from a hydrologic correct DTM with help of standard GIS functionality, flowaccumulation.

A hydrologic correct DTM means the DTM has been corrected in a way the calculated flow paths follow the actual rivers and streams.

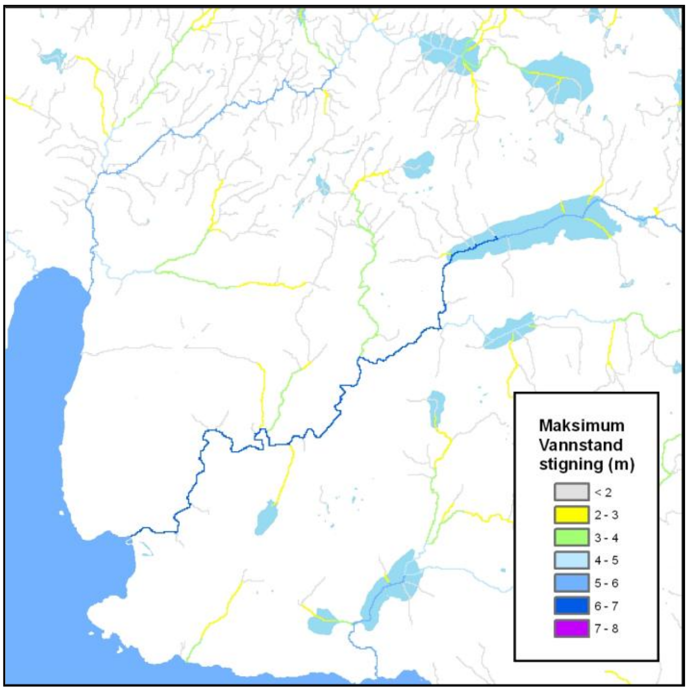
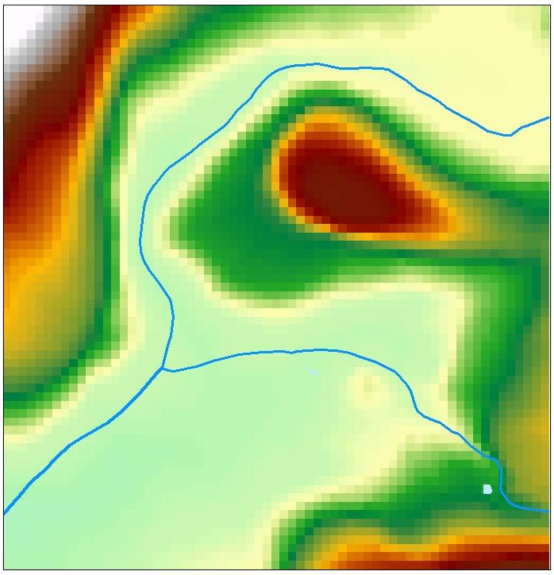


Fig 5. Calculated maximum waterlevels

A method has been developed to use the water levels to interpolate a flood plane. In regular floodplain analysis the rise in water level has been established through detailed hydraulic analysis using measured cross sections. By placing these values on the cross sections a floodplain can be calculated (interpolated). By overlaying the floodplain with a digital terrain model (DTM) the inundated area can be calculated.



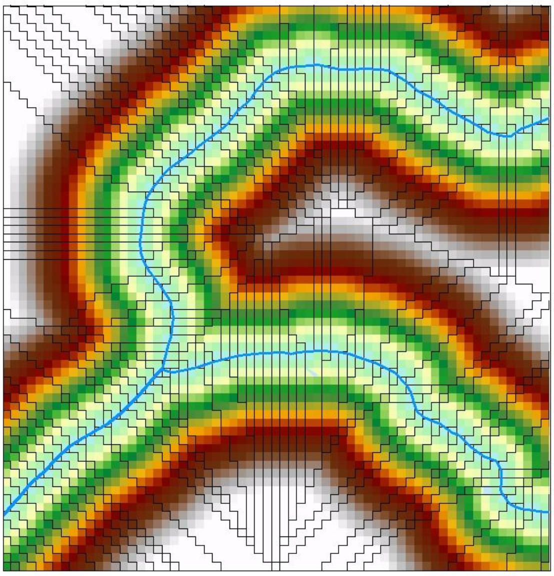


*Fig 6: The 25*25 m DTM*

Fig 7: The virtual DTM based on buffers and the "cross section" strokes.

A method had to be developed where a floodplain could be calculated without using cross sections. See figure 6. In Order to do this a set of 25m buffers is calculated around the rivers. The buffer number is then used as a height value (first buffer is 1m, second buffer is 2m etc) in a virtual elevation model.
The water divide in this virtual elevation model is situated on the highest elevations precisely in the middle between to river stretches. This further referred to as the virtual water divide.

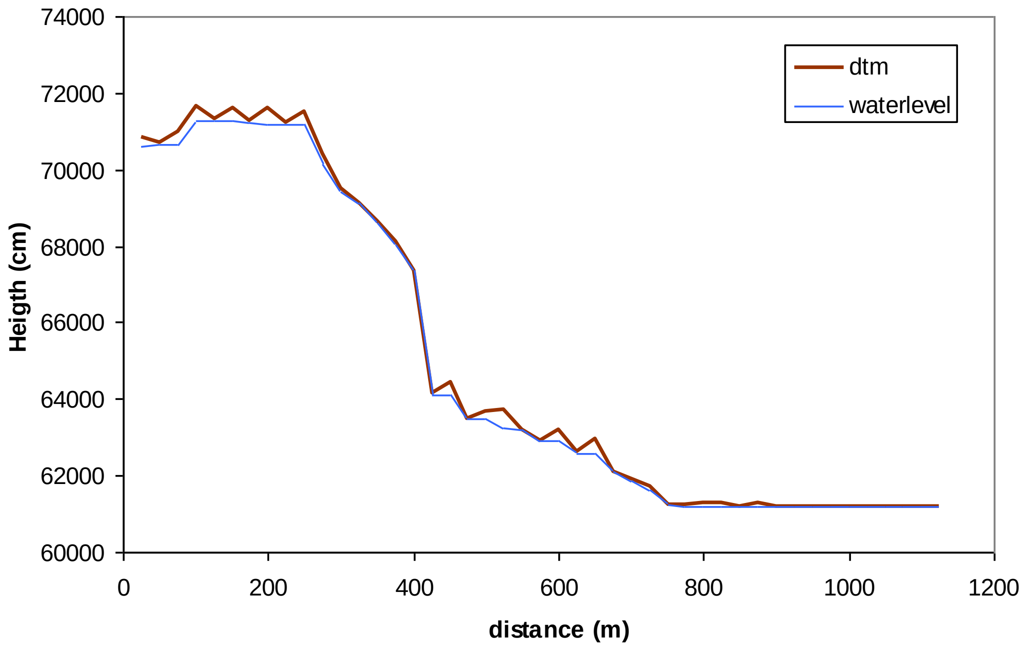


Fig 8: Water levels derived form the DTM

With standard GIS functionality the drainage pattern is calculated for this "elevation" model using the individual river grid cells as pour points. The result is a set of narrow strokes perpendicular to the river.
These strokes can be given the value of the highest water level along the river crossing the stroke. This value is derived from the digital terrain model. The water levels are corrected in a way they follow the terrain smoothly as shown in Figure 7.
Adding the maximum rise of water level gives a calculated flood level. By comparing this height with the height in the original terrain model the floodplain can be easily extracted.

Hydrology – Calculating inundated areas

Combining the flood plane with the Digital Terrain Model (DTM) it is possible to find the potentially inundated areas.
Doing this with the flood plane calculated with the method described above two fundamental problems have to be solved.

1) Water levels at the mouth of a tributary are not always dependent on runoff and field characteristics from its catchment area; they can be the result of inundating water from the main river.
2) The water divide of the "virtual" DTM lies beyond the actual water divide, resulting in false inundation planes.
   When the terrain is sloping down beyond the actual water divide to a level under the calculated flood level, it will result in a flooded area where the water physically can not arrive. When isolated, these areas can be eliminated.

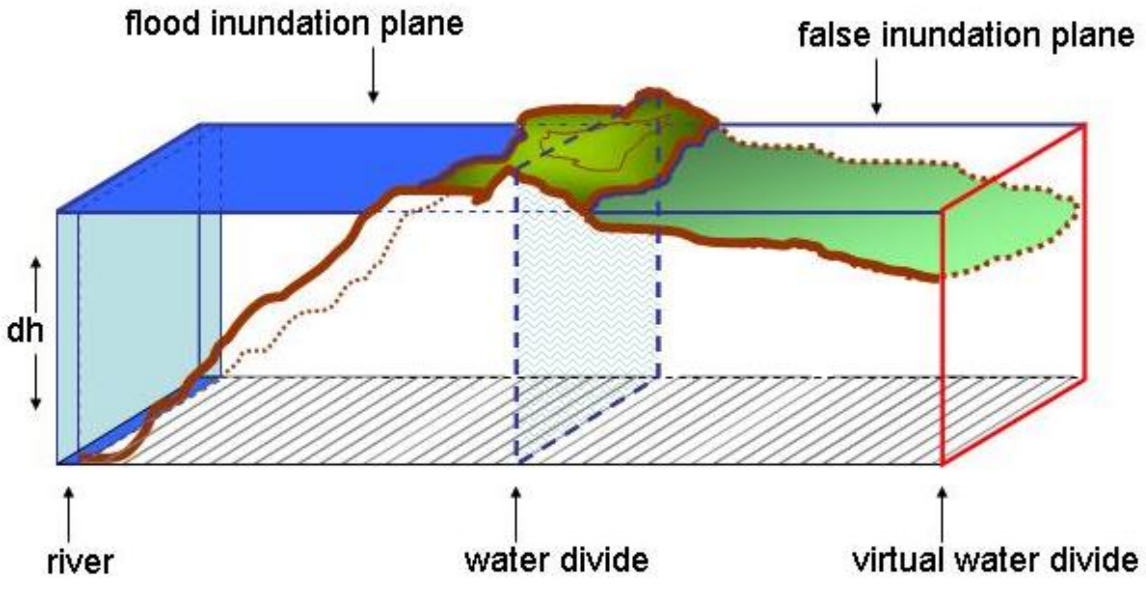


Fig 9: False inundation planes

But connected to a flood plane from another stream they can't be identified for elimination thus causing unwanted results.

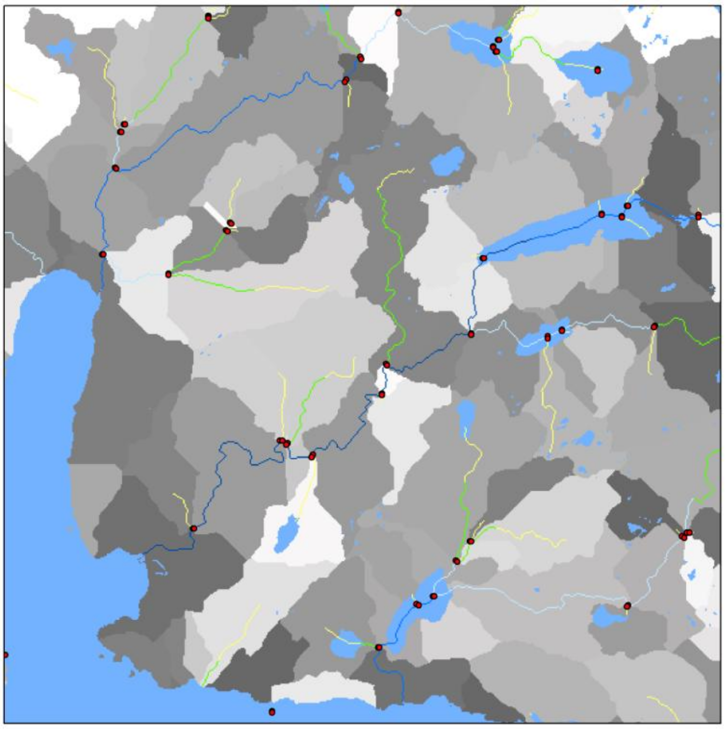
The opposite is also possible: When rivers lay very close to each other the "virtual" water divide can be closer to the river then the actual water divide. In these cases the extrapolation does not go beyond the "virtual" water divide thus causing an underestimation of the size of the flood plane.

The solution to the latter problem is to calculate flood plane areas for each and every river stretch separately:

- The false inundation planes can be identified because they are not connected to the river stretch and can be removed.
- The virtual water divide can only be closer to the river than the real water divide when the river stretch itself is meandering very much. This is normally only the case in a flat estuary. In these cases the difference in water level will be so small that the mistake is negligible.

This means that separate catchments have to be defined for every river stretch.
This is done in the following steps:

1) a river network is extracted from the flow accumulation grid, with a lower boundary of 1 square kilometre.
2) The river network is converted to lines and the end nodes are extracted.



3) The end nodes can not be used directly as pour points. Because two connecting lines (river stretches) have only one end node. When these are used as pour point to calculate the catchment, the catchment will contain two river stretches.

Fig 10. Pour points and catchments per river stretch

4) Using the flow accumulation grid, for each end node two new pour points are extracted lying one cell upstream in both river stretches.
5) These are then used as pour point to do determine the catchment for every river stretch separately.

Calculating inundation for each and every river stretch would make the program run to slow because of the vast amount of river stretches. Instead a 2 step method is applied where all river stretch catchments are divided into approximately 25 classes in a way that connection catchments get different class values. Using this we can calculate inundation for all watersheds in 25 iterations.

Flood level correction.

Having defined the pour points and separate catchments for each river stretch this can also be used to address the first problem that water levels at the mouth of a tributary are not always dependent on runoff and field characteristics from its catchment area; they can be the result of inundating water from the main river. Since we have a established relation between the "end nodes" and the pour points we can now use this to correct water levels form the pour point and upstream a tributary. The water level at the "end node", being of both river stretches has the maximum water level, being the level in the main river. This water level can be crossed over to the actual pour points of the catchments and accordingly to the whole catchment where it can be used to adjust all lower levels to this level. See fig 11.

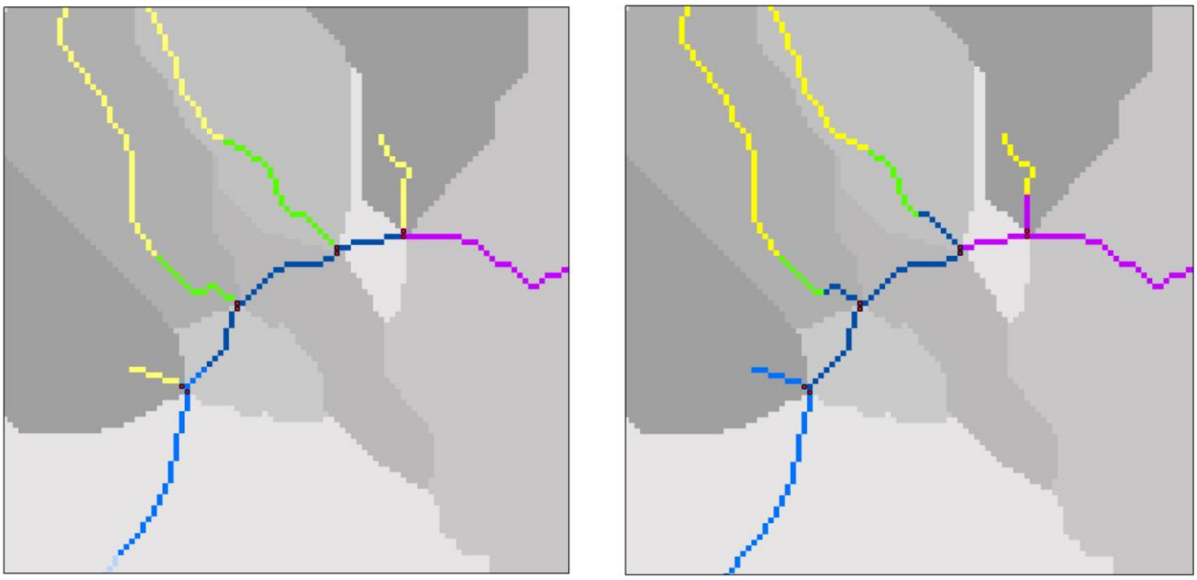
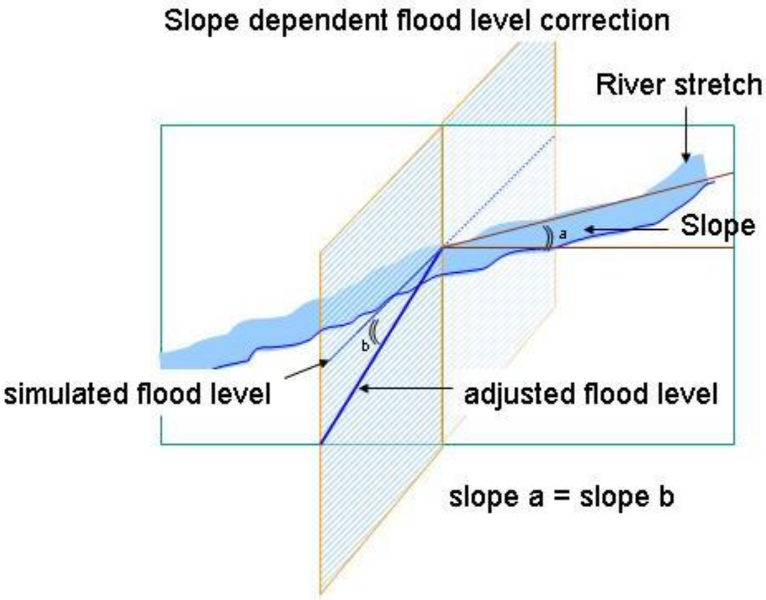


Fig 11. correction of water level at the mouth of tributaries

This flood water correction is done in several iterations to make sure that small branching contributories are sufficiently corrected upstream. The iterative correction stops when it all contributories are corrected or when 10 iterations are done. This is to avoid a mistake progressing uncontrollably upstream the system. The first iteration contains all contributories. The other iterations do not contain contributories of lakes, otherwise the water level of he whole lake will be corrected to water level at the outflow point, which would be wrong especially for long lakes which are abundant in the Norwegian landscape.

Flood plane correction

After assigning water levels to the virtual cross sections the water levels are adjusted to simulate the cross sections bending a little upstream. This is done to prevent water levels stretching out infinitely. This is a regular technique used in sloped terrain. In praxis we don’t bend the cross sections but the water levels. The technique that is used for bending the water levels is slope dependent.



The bending is considered to be the same as the slope. This is achieved by calculating the Tangent of the slope and calculating the decrease in flood level from this tangent and the distance to the watercourse (Euclidean distance). In flat areas the effect of the method is nearly none. While with an increase of the slope of the flood plane the water levels are bent more strongly. To avoid very local high distances to influence the bending, the slope is calculated on a smoothed terrain model (first mean then minimum values from 25 cells). This way the slope represents the general direction of the terrain.

By using the tangent and distance to the river to calculate decrease in flood level to much decrease is calculated in wide flat areas where the distance to the river is rather large, resulting in a to narrow flood plane. To compensate for this correction is recalculated using the flood plane from the first calculation to calculate the distance from. In steeper areas this will have no effect, however in flat areas this will lessen the calculated decrease in flood levels resulting in a wider flood plane.

Storm tide flood

A Flood susceptibility map should also include floods from storm tide water levels at sea. A new statistical analysis was done one tide water levels from 22 stations along the Norwegian coast with measurements from the ’50 up to 2009. The results are storm tide water levels for different return periods. These values were joined with a map of the tidal areas to create a storm tide map. The river floods levels are calculated as a worst case scenario, but without defining a specific return period. The storm tide water levels at a 1000 year return period were chosen as the worst case scenario. These water levels were extended land inward simply by scaling up.

The water levels were then combined with the DTM to calculate flooded coastal areas and finally these were combined with the river floods.

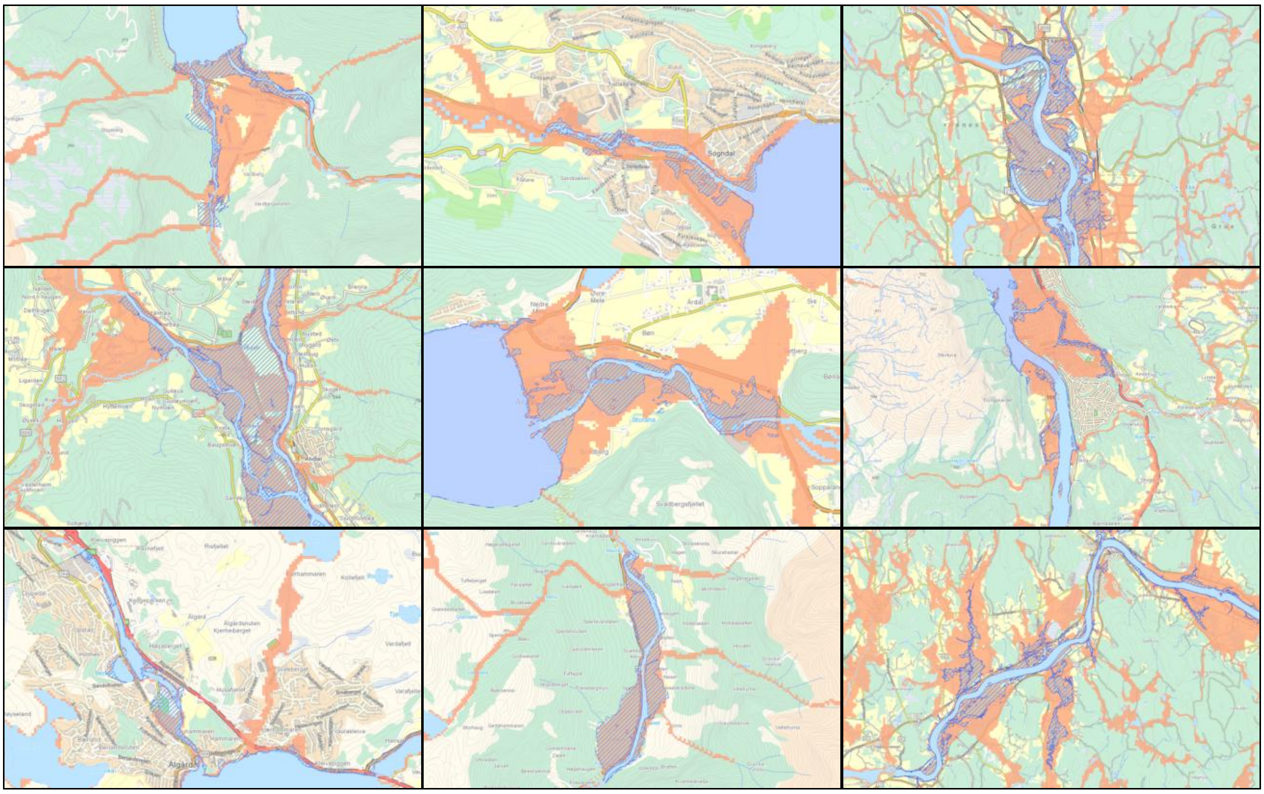
Hydrology – quality issues

While testing the method we generally found plausible results. However due to inaccuracy of the terrain model the results could locally be very wrong. Some routines were incorporated in the method to minimize the effects.

- Water levels are not taken directly from the terrain model. These are first smoothed to get rid of extremes.
- While making a virtual terrain model bases on the buffer distance per watershed a relative rare mistake is introduced. Watersheds that do not share a border can be treated at the same time because they do not interfere with each other. However in some cases two watersheds being in the same iteration can be located at a very short distance from each other (without sharing a border) so that while calculation the buffer distance to be used in the virtual terrain model the virtual water divide will be inside one of the watersheds. This might result in wrong water level calculations.
- While calculating "cross section" watersheds on the virtual terrain model the river network is used as pour point. In some cases parts of the actual watershed do not drain to the river when the virtual terrain model is used. This results in areas where no flood level is calculated. This mistake is corrected by assigning the highest flood level from the neighbouring cells within the watershed.
- Finally a sensitivity test was performed. By changing the maximum water level rise the effect on the extent of the flood plane was studied. The method proved to be very insensitive to changes in the maximum water level rise. The results of this sensitivity test can therefore be used to eliminate extremes. By comparing the width of the flood plane from a normal and a sensitivity calculation, locations are identified where an increase in water level rise has a big effect on the extent of the flood plane. These locations are either flat or the effect is a result of local inaccuracies of the DTM. By sampling both 500m down- and upstream we can differentiate between a local inaccuracy and a flat area. Extremes in the extent of the flood plane in case of local inaccuracy in the DTM are then corrected using the extent of the flood plane from the sensitivity calculation plus 2 times the standard deviation.

Validation

In order to assess the quality of the flood susceptibility map a validation was carried out where the results were compared with flood hazard maps from Flood Mapping Program. From the list of (about 150) flood hazard map every tenth project was selected. The results are shown below.



Discussion

The problems with underestimation and overestimation as were encountered with the geomorphological method do not occur in the hydrological method. Comparing the results with the results from detailed flood inundation maps, we find a very good match. The results show a larger inundated area compared with the detailed flood maps, but this is to be expected considering the flood maps show a 200 year flood event where as the continuance maps take the maximum possible water level rise as input.

All parameters that are used in the hydrological method have their own inaccuracy. In sum, this leads to a significant uncertainty in the results.

Some of the uncertainties and inaccuracies are mentioned below.

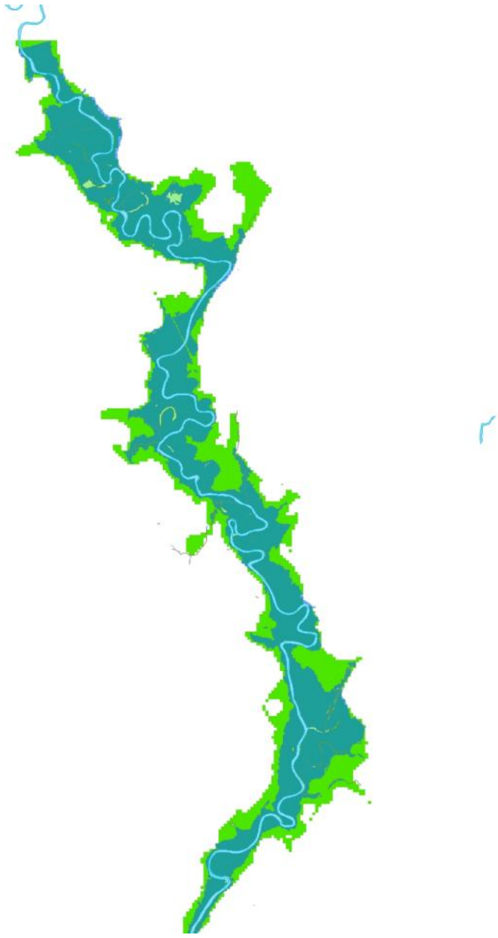


Fig 8: Results of the hydrological method compared with the calculated 500-year

- Accuracy of the used Terrain model /5/
- Use of Terrain model to obtain water levels
- Uncertainty in maximum rise of water level
- Implementation of regional different values
- Disregarding local hydraulic conditions (underestimation)

Despite of the inaccuracies in the DTM, it is usable in this method. The graph below shows a cross section of the terrain from a typical Norwegian valley. The dotted lines show the uncertainty in height values. The red lines show the cell size (25m).

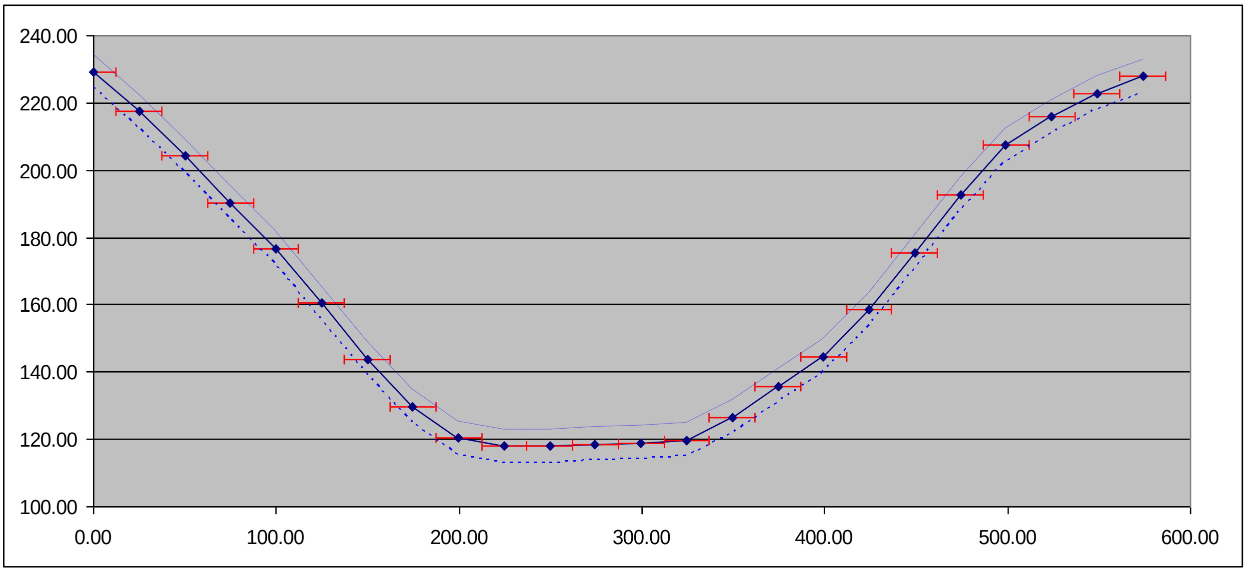


fig 9: Cross section from the DTM showing uncertainty in relation to cell size

From the graph is it clear that with a flood level up to 5m, the flat valley floor (6 cells or 150m) will inundate. An increase in flood level up to 10m will maybe only result in increasing the width of the flood inundation plane from 6 to 7 cells (175m). So because of the terrain form even a big uncertainty in the vertical will only result in a small uncertainty in the horizontal. This means that as long as we take a flood level that is an overestimation of the real maximum flood level we will find a relative good estimation of the flood plane.

The method is thus relatively insensitive to the exact water level rise. Inaccuracy in the calculated flood levels (water levels from the DTM + maximum water level rise) has therefore little effect on the result. This means it is not useful to use the more complex formulas to calculate the maximum water level rise.
For the same reason it doesn't seem to be useful to study the effect of using regionally differentiated formulas for calculating the maximum water level rise. Although this might result in a better correlation between maximum water level rise and area.

The Norwegian mapping authorities are in the process of establishing a new digital terrain model (DTM). The new DTM will have a better accuracy in elevation and probably a more detailed geometric resolution. When the new DTM is ready the methodology for defining areas exposed to flooding will be revised.

Conclusion

It is important to realize that the result of this method is not a flood inundation map. For that the method is not accurate enough. These maps can however be used as a continuance map. It does not show what areas can possibly flood. It shows areas where the danger of flooding needs to be further assessed.

Having said this the maps are suited for use in the small scale flood assessment as is required in the EU Food directive and as continuance map in the light of NVE's guidelines on spatial planning.

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