Development of a screening method to assess flood risk on Danish national roads and highway systems

Développement d'une méthode d'analyse pour évaluer le risque d'inondation sur les réseaux routiers et autoroutiers danois

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RÉSUMÉ

Une méthode d'évaluation du risque d'inondation sur les routes nationales danoises dans une vaste zone de la partie centrale et méridionale du Jutland (Danemark) a été élaborée pour la direction danoise des routes. L'une des raisons pour développer cette méthode est que le risque d'inondation a suscité un regain d'attention dû aux changements climatiques de ces dernières années et aux événements pluvieux extrêmes qui devraient être de plus en plus fréquents à l'avenir. L'évaluation était principalement fondée sur un modèle numérique de terrain (DTM) qui couvre 7500 km^2 avec une grille de 1,6 x 1,6 m. La haute résolution du modèle a été choisie afin d'obtenir une estimation précise des inondations potentielles pour les routes et leurs environs immédiats mais requerrait une exigence particulière pour les méthodes, matériels et logiciels. L'analyse a abouti à la réalisation de cartes détaillées (en couches GIS) illustrant l'emplacement de chaque dépression avec leur profondeur, superficie et volume. En outre, les chemins d'écoulements préférentiels, les limites des bassins et le classement de chaque dépression ont été calculés. Le classement est fondé sur le volume des dépressions comparé à un captage amont maximum et sur une analyse de sensibilité du coefficient de ruissellement. Enfin, une méthode d'évaluation du risque d'inondation à un niveau plus avancé (simulation hydrodynamique de surface et de drainage) a été développée et utilisée sur une zone inondable spécifique pour exemple. L'étude de cas montre que les bassins en amont, les dépressions, le système de drainage et l'utilisation des calculs hydrodynamiques ont une grande influence sur le résultat. Les bassins en amont peuvent contribuer grandement aux inondations.

ABSTRACT

A method to assess flood risk on Danish national roads in a large area in the middle and southern part of Jutland, Denmark, was developed for the Danish Road Directorate. Flood risk has gained renewed focus due to the climate changes in recent years and extreme rain events are expected to become more frequent in the future. The assessment was primarily based on a digital terrain model (DTM) covering 7500 square kilometres in a 1.6 x 1.6 m grid. The high-resolution terrain model was chosen in order to get an accurate estimation of the potential flooding in the road area and in the immediate vicinity, but also put a high requirement on the methods, hardware and software applied. The outcome of the analysis was detailed maps (as GIS layers) illustrating the location of depressions with depths, surface area and volume data for each depression. Furthermore, preferential flow paths, catchment boundaries and ranking of each depression were calculated. The ranking was based on volume of depressions compared with upstream catchment and a sensitivity analysis of the runoff coefficient. Finally, a method for assessing flood risk at a more advanced level (hydrodynamic simulation of surface and drainage) was developed and used on a specific blue spot as an example. The case study shows that upstream catchment, depressions, drainage system, and use of hydrodynamic calculations have a great influence on the result. Upstream catchments can contribute greatly to the flooding.

KEYWORDS

Flood risk maps, predicting flood risk of highway systems, high-resolution DTM, GIS analysis, sensitivity analysis, climate change, screening method, decision support tool

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1 INTRODUCTION

History has shown that extreme rain events can have a hazardous effect on roads, e.g. Berz et al (2001), Browering et al (2003) and Drobot et al (2007). Due to the new challenges from the climate in recent years; such as more frequent storms and intense rainfall, this subject has gained a renewed focus. In the summer of 2007 and 2009 many roads in Denmark were subject to severe flooding and this showed an immediate need to begin the work to secure and prepare the Danish roads to meet the challenges of climate change.

The effects of the climate changes have become one of the focus areas for the Danish Road Institute at Danish Road Directorate. The institute's theme "Climate & Environment" combines research and development projects with the aim to promote climate adaptation and environmentally friendly roads. Such roads are robust and functional, and ensure safety, passability, and durability. Focus is on minimizing the impacts and effects of already experienced and anticipated climate changes by protecting road constructions, equipment and buildings against collapse and by setting-up emergency plans in case of extreme weather conditions. Furthermore, the Danish Road Directorate plans to examine environmental issues related to roads, including the surrounding environment and use of eco-friendly materials (recycling and local materials), as well as securing the lowest possible energy consumption.

There are a number of scenarios for climate changes in Denmark that may influence roads and their surroundings (IPCC, 2007):

- Precipitation: More extreme and intense rainfall. Roads may become periodically flooded and impassable. It may be necessary to adapt the drainage systems or even change the location of roads.
- Wind: More frequent and stronger storms may cause implications for the passability of bridges. Increased wind power may also have a devastating effect on signs, masts, trees etc.
- Sea level rise: Increases in sea level may have implications for coastal roads already today. Future flood events could inundate the roads to an extent not seen before.
- Temperature: Denmark may experience more hot and dry summers, which may result in smoother roads due to hot asphalt.
- Groundwater: The groundwater table may vary more owing to wetter seasons with the risk of water leakage in the existing road construction.

These effects of extreme weather events are interdisciplinary in relation to both physical and administrative boundaries, e.g. Pahl-Wostl (2007). It is therefore essential to have an open dialogue and sharing of knowledge between the different units in Denmark, e.g. the municipalities, the Road Centers and the Danish Road Directorate. It is necessary to make both long-term and ad hoc plans for investments to address these challenges, and to have similar priority models so that problems are solved on the same basis even at different locations. This can also help develop a best-practice guideline for adaptation and strategies for different situations.

The national strategy for the coming years will focus on the following:

- Upgrading the drainage systems
- New guidelines for road construction, better and greater awareness in exposed locations
- Forecast and prevention of deterioration of road foundations
- Surveillance systems and emergency plans
- Mapping locations with historical flooding events of roads

It is, however, important to point out that because of the long durability of roads and high costs of rebuilding, it is important to use sustainable, long-term planning. Tools are needed to help facilitate this process and prioritize the effort when adapting to climate change. Therefore, the Danish Road Directorate is participating in the ERA-NET ROAD- project SWAMP (Stormwater prevention – Methods to predict damage from the water stream in and near road pavements in lowlands areas). The project aims to find ways to identify flood risk areas and provide instructions on the kind of details that should be included when dealing with the drainage systems. The task is performed in corporation with the VTI, Statens väg-och transportforskningsinstitut (Swedish National Road and Transport Research Institute).

This paper will describe the development of methods for screening large areas and results from the SWAMP project. The potential high risk areas are identified by analyzing detailed topographic data and material presented on maps. When planning new roads, the map can be applied in the planning phase for determining whether there is a risk in that area. It can be examined whether emphasis should be on water control in critical situations or on the implementation of traditional emergency plans.

2 MATERIALS AND METHODS

Damaging effects of road flooding in Denmark can be divided into 3 groups:

- Water on the surface are collected in depressions in low lying areas owing to insufficient capacity in the drainage system. The contributing drainage areas can be the surrounding areas as well as direct drainage on the road
- The flooding of rivers caused by insufficient downstream capacity
- Flooding of low lying areas owing to rising sea level

In this study we present a method which can identify flood sensitive areas in the road network. We refer to these as blue spots and they are defined as areas where flooding is expected to take place in case of extreme rainfall. The blue spots can be identified on the basis of previous experience, but new spots will appear on the road network, when precipitation increases. The analysis is divided into three levels where each level helps to provide a better overview of the actual flood risk. As knowledge increases gradually, the numbers of risk areas are reduced. The work presented in this paper is based on the 3 levels on modelling shown in Table 1. Focus is on levels 1 and 2 and the method is implemented around national roads in the area shown in Figure 1. The outcome is used as a tool to prioritize the efforts needed for adaption.

LEVEL 1 - Screening using terrain analysis
• All the blue spots are identified. Assuming a runoff coefficient of 100% in the catchment. No drainage capacity is included, e.g. Zerger (2002). • Low-lying areas at risk from flooding due to rising sea level are identified. A sea level rise of 1, 2 and 3 m are used. Dikes are included so no flooding can occur behind dikes unless water levels exceed the dike height. Gradients in streams are neglected.
LEVEL 2 – Frequency of flooding is calculated for blue spots
• Preferential flow paths and catchment areas for each blue spot are calculated, e.g Maksimović et al (2009). • Simple calculation of flood risk from contributing areas. "Risk map" with the precipitation needed to fill low-lying areas is created. Assuming no drainage between blue spots.
2.1.1 LEVEL 3 - Hydrodynamic model of surface reservoirs and depressions
• 1d-1d Coupling between the surface (terrain, canals and ponds) and drainage systems (pipes), e.g. Boonya-aroonnet (2007), Jensen et at (2010). • 2d-1d Coupling between surface and drainage systems e.g. Nielsen et al (2008), DHI (2009), Wallingford (2009), Domingo et al (2009).

Table 1. Levels of analysis used in the study.

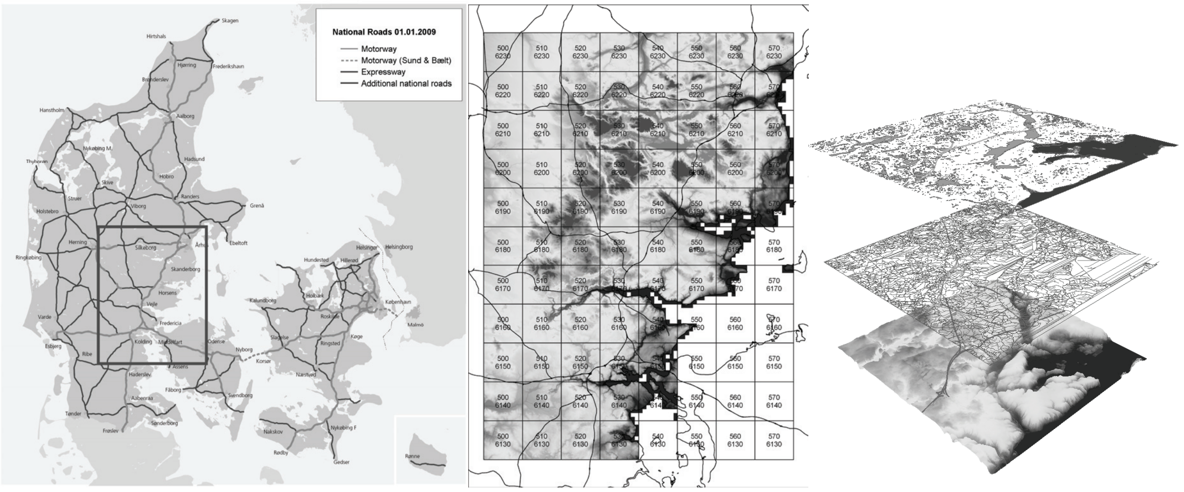

Figure 1: Study area and data. In this area there is a total of 875 km of national roads. Total length of all national roads in Denmark (January 2009) was 3790 km.

Furthermore, an example of an analysis of level 3 using 1d-1d modelling is included. Mike Urban was used as the hydrodynamic 1D model (Mike Urban, DHI 2010). Water was routed between the blue spots by pathways Iidentified in the DTM. A Manning number of 30 $m^{1/3}/s$ was used representing rough surface runoff (Davis, 1952). As no information was available on the pipe network this was neglected. Instead, sensitivity analysis is made on the drainage capacity. In Denmark, natural drainage is recommended to 1 l/s/ha (geometric area). This was implemented in each blue spot in the upstream catchment. Calculations were made using a Chicago Design Storm (CDS) with a return period of 100 and 500 years. A concentration time of 14 minutes was used for each catchment. A “climate factor” of 1.4 representing the factor difference in rainfall due to climate change was included in the calculations. The recommended factor in Denmark is between 1.2-1.5 depending on the return period (Arnbjerg-Nielsen et al 2008).

The benefits of implementing level 3 are that the water flow on the surface as well as in the drainage systems can be taken into account thus providing a more accurate calculation of the flood risk. Level 3 is an excellent tool to use when identifying a solution that includes more details about the systems (e.g. drainage and storage capacity) or when setting-up emergency plans.

2.2 Data used in the analysis

The basis of the calculation of the flooding risk areas is LiDAR data for a large part of Mid-Jutland. The elevation data is available as a Digital Terrain Model (DTM). The coordinate system is UTM zone 32N and the vertical reference system DVR90. There has been no scanning during periods of major crops, snow and major quantities of melt water.

The elevation data is provided by the Danish Road Directorate in 75 parts of 10x10 km. The grid data is available with the 1.6 m point density (commonly used in Denmark) and a height accuracy of better than 10 cm at well-defined surfaces. Each part of 10x10 km thus consists of 39,062,500 points. The whole model is 2.9 billion points, which imposes high demands on methods, tools and hardware. The calculations are performed in hardware with 2.33 GHz (quad core Xeon CPUs), FX3450/4000 graphics card (256 mb) and 4 GB of physical memory. The analysis is performed at the highest level of detail equal to the density of the LIDAR data (1.6 x 1.6 m grid). To perform the analysis in this project, it has been necessary to divide the total terrain model (7500 km^2) in 3 parts. This is done out of consideration for the calculation speed and limitations in the software applied.

It should be noted that the DTM reflects the date when the overflying was done (2006-2007). So modification of the terrain as a result of road projects will affect the outcome of the analysis. There are several ongoing and planned road projects in Road Centre Jutland and Road Centre Southern Denmark.

There are areas in the terrain model that are missing data ("null value"). This may affect the results of terrain analysis. It has been chosen not to correct the data (e.g. by interpolation), because it is assumed that there is little overlap with national roads.

2.3 Data Processing

Risk areas are identified solely on the basis of depressions in the terrain. Ranking in relation to return periods for flooding, basin area, soil conditions and possible transport through drainage systems is thus not included. Only depressions with a minimum volume of 10 m^3 are included in the study.

Blue spots are identified by filling all depressions, and then calculating the difference in height compared to the original terrain. The spatial distribution and size of depressions are obtained. In addition, the calculated volume of the depression is achieved.

Bridges over water features, roads or railroads often remain in the DTM and bridge removal is therefore necessary when doing flood modelling. If bridges are not removed they will appear as "dikes" where water is likely to accumulate and create false blue spots. GIS layers containing information on locations of bridges on the national roads in Denmark were used to assess this. Furthermore, maps with locations of streams and rivers together with orthophotos were applied. In some locations the bridges have already been processed by the supplier.

Underpasses of piped rivers and streams will also appear as obstacles in the terrain model. These barriers are removed as well. It should be noted that within the project's framework it has not been possible to identify all piped river stretches. Figure 3 shows an example of the effect of the inclusion of these underpasses. If the underpasses are included and the DTM is modified along the highway, then the water can pass leaving no blue spots.

In total 221 bridges and other crossings have been identified, of which 98 have been reported by the Danish Road Directorate.

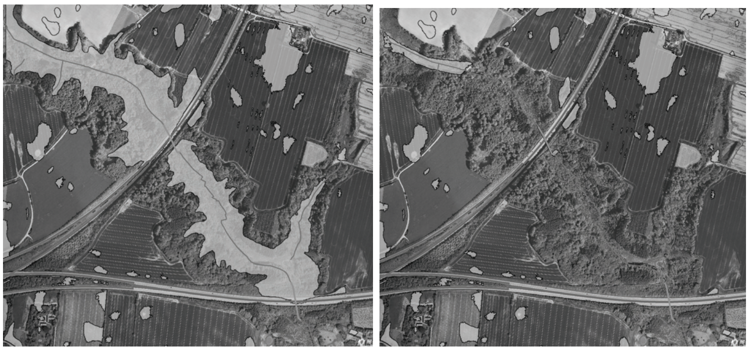

Figure 3. Blue spots before the barrier in the DTM is removed around Soenderjyske Highway and Taulov motorway (left). Distribution of blue spots after an underpassing has been introduced in the DTM (right).

The effect of sea level rise is assessed by the use of the DTM and a water level value representing the sea level conditions being analysed. The terrain model provides information on where the water from the sea can move into the coast, accumulate and cause damaging flooding. The depth of flooding in a cell is computed by subtracting the land elevation from the water level.

For the calculations in Level 1 and visualization of results, a method was developed applying the facilities in the ArcGIS environment (Desktop, Spatial Analysts, 3D Analyst, etc.). In addition, a number of other tools for analysis, including add-on programs for ArcGIS Desktop, and proprietary programs that make it easier to handle large volumes of data were developed.

3 RESULTS AND DISCUSSION

The following are the results of the various themes which were calculated for the study area. The themes are in sets of polygons, polylines and raster (grid files). The themes do not depend on a specific GIS system, which is an advantage owing to the different platforms applied for the planning purposes.

3.1 Sea level rise

Three scenarios for future sea level rise are assessed. The results are shown as polygons for the areas which are flooded indicating a sea level rise of 1, 2 or 3 m. The maps are based on the assumption that water will not be able to flow into areas that are topographically disconnected from the coast.

Figure 4 shows the results of calculations where seven potential risk areas have been identified. The Figure shows how water can spread inland, if the water level rises in the Vejle Fjord. In the future, the sea level is likely to increase due to climate change and the likelihood of high water levels would also increase. The areas of national roads that will primarily be affected by sea level rise, lie in the cities of Fredericia, Horsens, Kolding, Aarhus and Vejle.

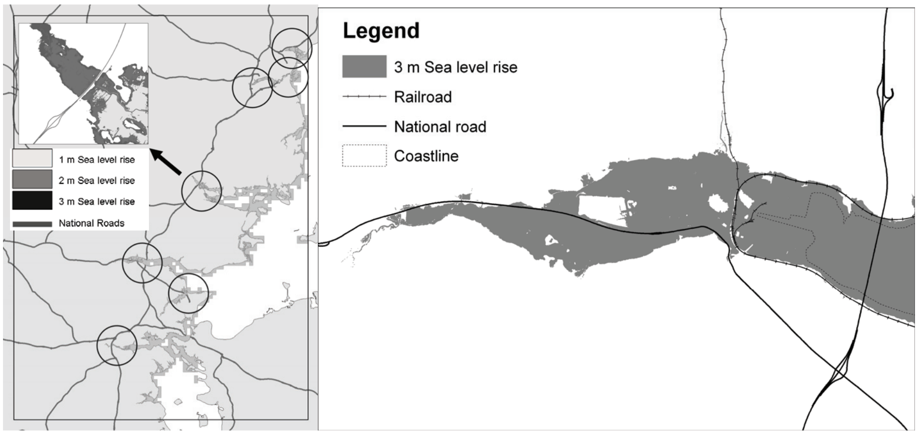

Figure 4. Calculated sea level rise and potential blue spots and zoom showing sea level rises of 1, 2 and 3 m (left figure.). Zoom on city of Vejle with sea level rise of 3 m (right figure.).

3.2 Depressions, preferential flow paths and catchment area boundaries

All depressions with a volume higher than 10 m^3 are extracted from the calculation as polygons. This is considered as an appropriate level of detail. Information on area and volume are stated in the tables of attributes belonging to the theme. Calculations are made with the highest level of detail (1.6 x 1.6 m) around national roads (1 km buffer), and a coarser resolution for the entire elevation model (4 x 4 m).

When identifying the blue spots it has been assumed that all surfaces are impermeable with no possibility of transport or runoff via the drainage system. The map shows potential risk areas - namely depressions in the terrain where water may accumulate and cause flooding. The map material shows the distribution of blue spots with information about size and volume of the depression, and maximum depth.

Figure 5 shows an example of the calculated maximum depths. Calculations are made for the entire terrain model in the highest resolution, corresponding to the depths shown in Figure 5.

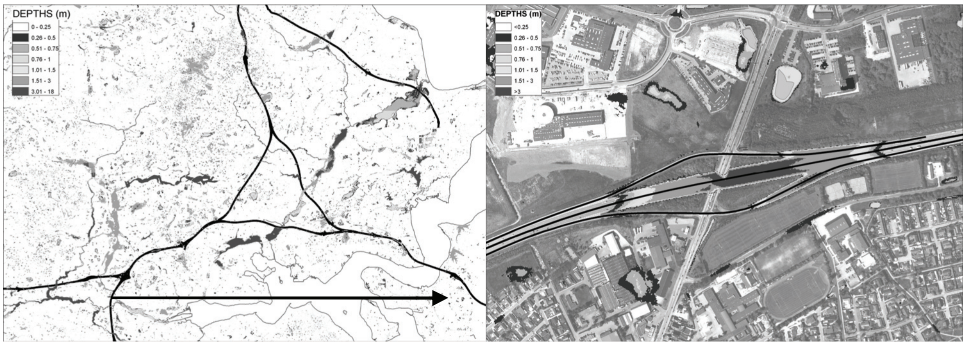

Figure 5. Examples of blue spots, which has information about area, volume and depth.

The DTM was used to calculate preferential flow paths and catchment boundaries. This gives information on how water is transported on the surface from depression to depression, and the geographical distribution of the associated catchments. Initially, a minimum threshold for the waterways of 1 ha was selected, so pathways with an upstream surface area less than 1 ha are not included. For each depression greater than 100 m^3 a catchment area is calculated if the upstream area is at least 1 ha. Figure 6 shows the preferential flow paths and the basin boundaries to the same depression.

Waterways and catchment boundaries were initially calculated for an area equivalent to 1 km from the centre of national roads. As the catchments and depressions found had a far greater spatial distribution, it was decided to calculate catchments and waterways for the entire terrain model.

The frequency of flooding on national roads is assessed at a general level, taking only the adjusted terrain model into account in the analysis (underpasses included). The theme is depressions greater than 100 m^3 with indication of how many millimetres of rain needed to fill up the depressions. The runoff is estimated equivalent to runoff coefficients of 20 -, 40 -, 50 -, 60 -, 80 - and 100% of the catchment. It is assumed that there is no exchange of water between the catchment areas, so each depression and associated catchment are considered separately. Furthermore, storage in small depressions (<100 m^3) is not included within the boundaries of the catchment and in depressions greater than 100 m^3 with a catchment less than 1 ha, if one exists.

Given that depressions and associated catchments are determined, the volume may be related to the size of the catchment. A large catchment area with a small blue spot provides a greater risk than a small catchment with a large blue spot. Precipitation needed to completely flood the blue spot, can be calculated by dividing the depression volume with the reduced catchment area. Depressions can be coloured according to the calculated precipitation, e.g. depressions may be coloured in red if it should be explored further, as it takes less than 25 mm of rain to fill them up. Figure 6 shows an example.

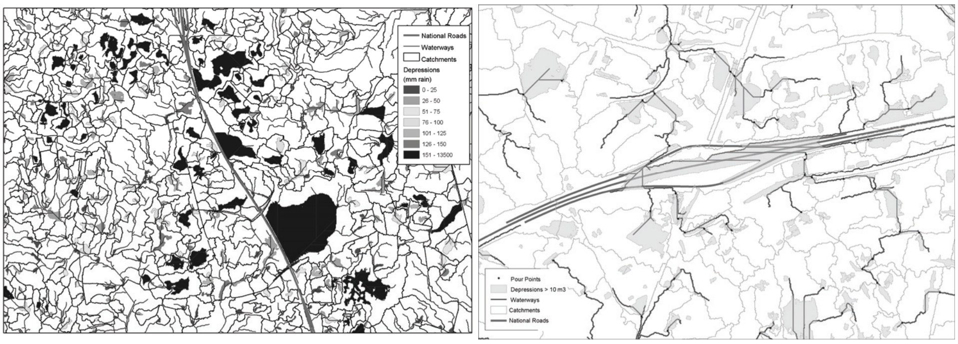

Figure 6. Waterways and catchment areas for a region at the Soenderjyske motorway between Kolding and Fredericia (left). Depressions with flood risk illustrated by the precipitation needed to fill the depression (right).

After a prolonged wet period, the risk of surface runoff from the surrounding catchments is higher. The attributes associated with the GIS theme is rain depth calculated for different levels of imperviousness (20-40-50-60-80-100%). It can be used to assess the sensitivity of the depression in proportion to the area, which contributes to the runoff. Figure 7 shows millimetres of rain with a runoff coefficient of 20% and 100% respectively.

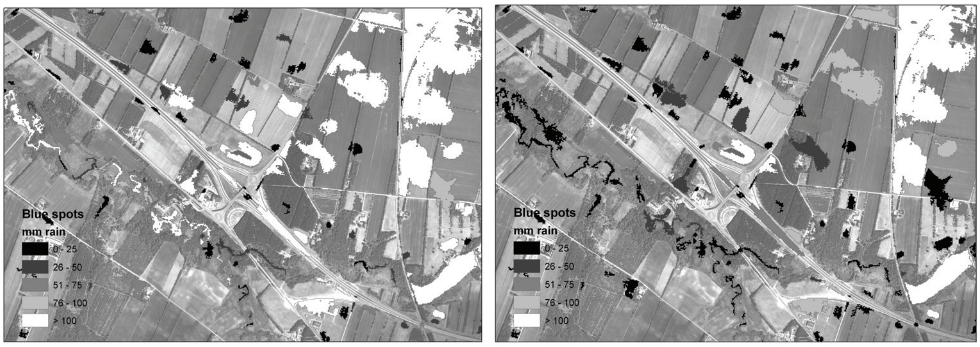

Figure 7. Runoff coefficient 20% (left) and runoff coefficient 100% (right)

3.3 Example of a flood analysis at level 3

In the following a calculation was made at level 3 for an area with risk of flooding. The area is located near Brande, Jutland with a local depression of approx. 1700 m^3 directly on the road with a maximum water level of 0.5 m. A detention basin is placed downstream (~2600 m^3). The contributing area upstream of the depression in road space has been identified; see Figure 8. The runoff coefficient, roughness coefficient etc. are estimated data. The data derived from levels 1 and 2 according to Table 1 have been applied. Mike Urban was used to calculate the flooding of a 100-year and a 500-year event (Chicago Design Storm) with and without climate factor.

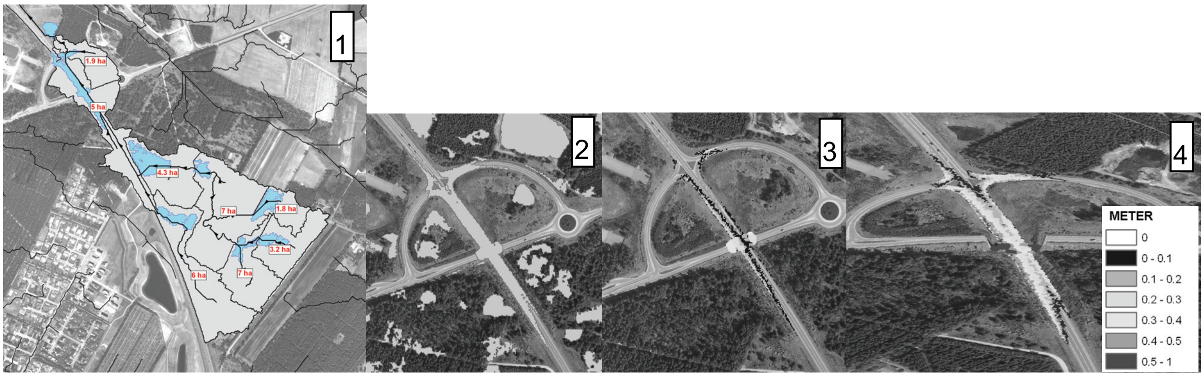

Figure 8. Risk area identified (1). Depression using level 1 (2). Calculated maximum water depth for T = 100 years (3). T=500 years (CF=1.4) (4).

Below are listed the results of the rain events with and without climate factor (Table 2). E.g. a 100-year rain without climate factor gives a maximum depth of water in the depression of 32 cm and a maximum flow of 229 l/s, a cumulative flow to the depression of 817 m^3 and no contribution from upstream depressions. A maximum speed on the surface was calculated to 0.7 m/s. For events with a large return period, the depression will be flooded and upstream areas are contributing to the inflow. This shows how important it is to include all the potential drainage areas and not just the direct drainage on the road. The model was used to make sensitivity analysis of the drainage capacity of the road by calculating different retention times depending on the drainage capacity.

Scenario	Max. depth (cm)	$Q_{max,inflow}$ (l/s)	Acc. volume (m^3)	From upstream (m^3)	Max vol. (m^3)	Retention time (5 l/s)
$T_{100\ year}$	32	229	817	0	425	24 hr
$T_{500\ year}$	39	323	1232	175	720	40 hr
$T_{100\ year}$ (CF=1.4)	40	323	1310	211	771	43 hr
$T_{500\ year}$ (CF=1.4)	59 *)	436	2900	1482	1700 *)	94 hr

Table 2. Results for events with and without climate factor. *) Depression is filled.

Figure 8 shows the calculated maximum water depths. As illustrated by the figures, the flooded area under the bridge deck has larger extent than the width of the road. This is owing to the bridge deck having been removed in the original terrain model, see previous. The z-levels under the bridge are not valid, and the calculated volume and water depths will be affected. The fact that less volume is available in reality will lead to a wider dissemination of the flooding.

For a return period of 500 years the low lying area under the bridge will be completely filled and water will start to run downstream. Very detailed boundary conditions such as the shape and height of the curves may completely change the surface flow paths. A resolution of 1.6 x 1.6 m used in this study may result in an inaccurate description of roads. This can be compensated by lowering the road in the terrain model.

3.4 Flood risk maps

The results of the calculations are illustrated in maps showing the critical flood areas. Figure 9 shows spots which may be critical areas. Spots are underpasses, depressions in the road area and depressions which have a distance less than 10 m from the middle of the road. More information on the actual flood risk can be found by reviewing the levels 2 and 3 in the analysis.

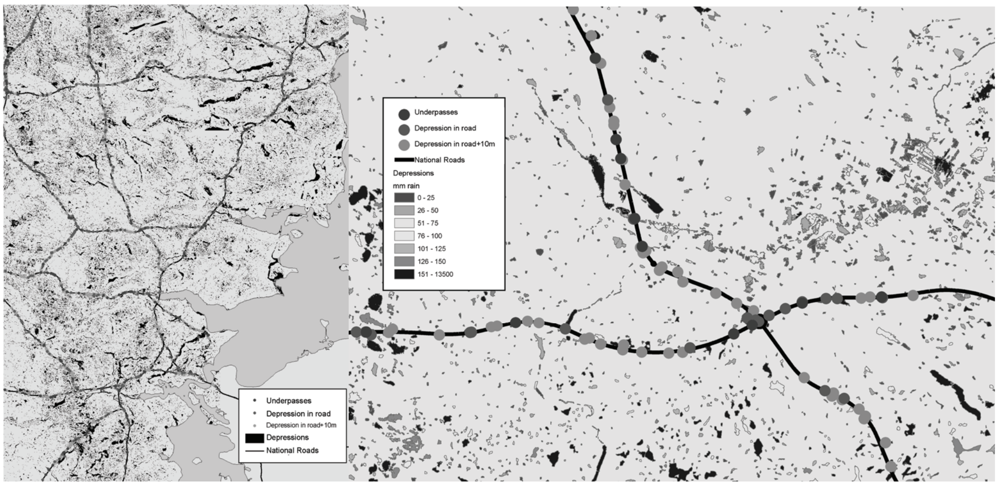

Figure 9. Critical areas (left) and an example of how to prioritize in relation to precipitation.

Flood maps could be used as part of a ranking of the depressions in relation to the risk of flooding. Areas with high risk of flooding can be given higher priority compared to areas with less or no risk of flooding. The priority could be made from the position of the depressions in relation to the road area, and how many millimetres rain needed to fill the depressions.

After pointing out all the blue spots on the road network on a level 2 basis, it is often necessary to minimize the numbers of blue spots for further evaluation. This can be done by a risk analysis as illustrated in Table 3. The table shows the matrix of a simple risk analysis in which the left column states the probability of an event e.g. some of the rain fall events will probably never happen, e.g. between 151-13500 mm/day as shown in Figure 10 to the right. This type of event can be categorized as ‘Unlikely’ or ‘Rare’, using Table 3. The consequences for the road users and the roads are illustrated at the top row in Table 3. The same rain fall event can have different consequences for different type of roads. The number of road users can also have an influence on the consequences, e.g. stopping 500 road users due to a blue spot does not have the same consequence versus stopping 5000 road users.

After each blue spot has been categorized with a ‘probability’ and a ‘consequence’, it can be plotted in the matrix in Table 3. All blue spots plotted in the red area of the matrix are road network areas in the ‘high risk’ end of the scale and should be the blue spot areas for a further evaluation using Level 3 as described in this paper. Some of the blue spots plotted in the orange area of the matrix are questionable for a further evaluation, but even ‘Unlikely’ events can turn out to have a ‘Catastrophic’ effect and may be further evalulated by a level 3 analysis.

	Insignificant	Minor	Medium	Major	Catastrophic
Certain	🟧	🟧	🟥	🟥	🟥
Likely	🟨	🟧	🟧	🟥	🟥
Possible	🟩	🟨	🟧	🟥	🟥
Rare	🟩	🟩	🟨	🟧	🟥
Unlikely	🟩	🟩	🟨	🟧	🟧

Tabel 3. Risk analyse matrix. The probability is stated in the left column and the consequences are specified in the top row.

The data from the flood maps and the risk analysis allow for the establishment of a contingency plan for extreme situations. It can provide valuable information about the measures to be taken to reduce damage, if and when extreme events occur. If the flood maps and the risk analysis are applied, all blue spots can be evaluated and efforts can be focused on a few blue spots lying in the ‘high risk’ end of the matrix which will save time and be more cost-effective.

4 CONCLUSION

This paper describes a method for screening large areas of flood risk on national roads in Denmark. The analysis is divided into 3 levels where each level provides a better overview of the actual flood risk. Level 1 is a raw analysis of terrain data to identify local depressions, level 2 focuses on risk assessment of the contributing catchment areas and frequency of floods, while level 3 includes detailed hydrodynamic modelling of the surface flow. As knowledge increases gradually with the different levels, the numbers of areas of risk are reduced. The method was tested and applied on a large area in the middle and southern part of Jutland. The outcome of the analysis was valuable flood risk maps that will help prioritize the efforts as the road sector adapts to climate change.

Focus has been on levels 1 and 2 of the proposed method. These screening methods will greatly improve the knowledge about flood risk, but are not suited for more detailed modelling of flood dynamics. Here, it will be necessary to include level 3. This was illustrated on a test area in Brande, which illustrates how detailed modelling can be used to increase knowledge of the system and show the importance of coupled surface runoff from depressions further upstream. The proposed method can be applied to all areas in Denmark as well as in other countries where relatively high resolution elevation data is available. High resolution DTM will give planners a much more accurate representation of ground surface elevation and will enhance the accuracy of the extent of the predicted flood and the tools created. A tool is now available for long term investments as well as ad hoc solutions based on the same priority model.

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