SWAMP

The Blue Spot Model

• development of a screening method to assess flood risk on national roads and highway systems

Report 3

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Report 3 – The Blue Spot Model

- **development of a screening method to assess flood risk on national roads and highway systems**

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Preface

The SWAMP project is part of an ERA-NET ROAD initiated transnational research programme called "Road Owners Getting to Grips with Climate Change". The four projects commissioned under this programme are funded jointly by the road administrations of Austria, Denmark, Finland, Germany, Ireland, Netherlands, Norway, Poland, Spain, Sweden and United Kingdom. The other three projects are:

IRWIN: Improved local Road WINter index to assess maintenance needs and adaptation costs in climate change scenarios

RIMAROCC: RIsk MAnagement for ROads in a Changing Climate

P2R2C2: Pavement Performance and Remediation Requirements following Climate Change

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1 Introduction

Climate conditions are generally considered when designing roads but have gained a renewed focus due to the challenges from the climate in recent years; such as more frequent storms and more intense rainfall. Effects of climate change have become one of the focus areas for the National Road Authorities. Focus is on minimising the impacts and effects of the already experienced and anticipated climate changes to ensure safety and passability. This means that road constructions, equipment and buildings are protected against failure and that there is an emergency plan in case of extreme weather conditions.

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

Precipitation: More extreme and intense rainfall. Roads can become periodically flooded and impassable. It may be necessary to adapt the drainage systems or possibly change the location of roads.
The three scenarios, presented in Table 1, extrapolate the precipitation situation in the northern part of Europe. Two of the scenarios are from the IPCC: A2, which is a medium to high scenario and B2, which is a medium to low scenario. The scenarios of the IPCC are largely based on a socio-economic projection of the global increase in population and the accompanying discharge of greenhouse gasses, which influence the predicted climatic changes.

The third scenario is based on the EU's objective that global warming must not exceed 2 degrees Centigrade in relation to pre-industrial time. The scenario is therefore known as EU2C.

It can be noted from Table 1 that in the period 2071-2100 there will be an increased maximum daily precipitation of 20 %, irrespective of scenario. Already at the present point in time, only two years after the IPCC published its most recent extrapolation report, the question is being raised whether 20 % is sufficient and it is most likely an underestimate (amongst others the Danish Meteorological Office of 13/8 2008 states: The extreme will be more extreme.)

Table 1. Prediction of the increase/decrease of precipitation in the northern part of Europe

IPCC Scenario	A2		B2		EU2C	
Year	2006-2035	2071-2100	2006-2035	2071-2100	2006-2035	2071-2100
Yearly precipitation	+2 %	+9 %	+2 %	+8 %	+0 %	+0 %
Winter precipitation	+8 %	+43 %	+6 %	+18 %	+0 %	+1 %
Summer precipitation	-3 %	-15 %	-2 %	-7 %	-2 %	-3 %
Max. daily precipitation	**+4 %**	**+21 %**	**+5 %**	**+20 %**	**+11 %**	**+22 %**

Sea level rise: Increases in sea level may have implications for coastal roads already today. Future flood events could flood the roads to an extent not seen before.

Temperature: The northern part of Europe can get hotter and drier summers, which means softer asphalt.

Groundwater: Groundwater tables can vary more due to wetter autumn, winter and spring, with risk of water leakage into the existing road construction.

Wind: More frequent and stronger storms may have implications for passability of bridges. Increased wind power can also have a devastating effect on signs, masts, and trees etc.

The effects of temperature, groundwater and wind are not further discussed in this document.

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 share knowledge between the different administrative units, not only on a national level, but also on an international level. 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 at different locations. This can also help develop a best-practice guideline for adaptation and strategies for different situations.

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). The strategy for the coming years will likely focus on the following:

- Evaluating, and where necessary, upgrading the drainage system of roads
- New guidelines for road construction, increased awareness in exposed locations
- Forecast and prevention of deterioration of road foundations, due to intensive rainfall
- Surveillance system and emergency plans
- Mapping road locations with a history of flooding

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. In order to minimise the hazardous floods and prioritise the effort when adapting, it is necessary with an overview of potential risk areas. This part of the SWAMP project aims to find ways to identify flood risk areas and provide instructions on what kind of details should be included, when addressing the drainage systems.

The potential high risk areas can be identified using detailed topographic data and material presented on maps. By planning new roads, the map can be used in the planning phase for determining whether there is a risk in that area. Regulation of the terrain can be necessary in existing areas and establishing of targeted preparedness can be developed, so the economic and societal consequences of the hazardous floods are reduced significantly. The analysis performed can be used to decide where to start the effort to prevent and limit damage. In each case, it can thus be evaluated whether there should be emphasis on controlling the water in critical situations or use traditional emergency plans.

2 Methods

In this study, three events/processes that can cause flooding of roads are considered:

- Water accumulates in depressions due to lack of capacity in the drainage system (or perhaps lack of drainage system at all!). The contributing drainage areas can be upstream catchments, as well as direct drainage from the road
- The flooding of rivers, caused by insufficient downstream capacity
- Flooding of low lying areas by 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 report is based on the three levels of modelling shown in Table 2.

Table 2. Level of analysis

LEVEL 1 – Screening using terrain analysis

• All the depressions are identified. Assuming a surface runoff of 100% in the catchment (i.e. no infiltration of rainwater into the soil), e.g. Zerger (2002). See Figure 1.

• Low-lying areas where there is danger of flooding due to rising sea levels are identified. Different levels of sea level are used. Dikes are included so that no flooding behind the dikes occurs unless water levels exceed their height. It takes no account of gradients in streams.

Figure 1. All depressions are identified assuming 100% catchment runoff and no drainage in the depression.

LEVEL 2 – Rain sensitivity for individual depressions

• Flow paths and catchment areas for each blue spot are calculated, e.g. Maksimović et. al. (2009).

• Simple calculation from contributing areas. "Risk map" with the amount of precipitation needed to fill low-lying areas. Assuming no drainage from depressions. Rain sensitivity analysis with impermeability of the catchment area of 20, 40, 50, 60, 80 & 100%. See Figure 2.

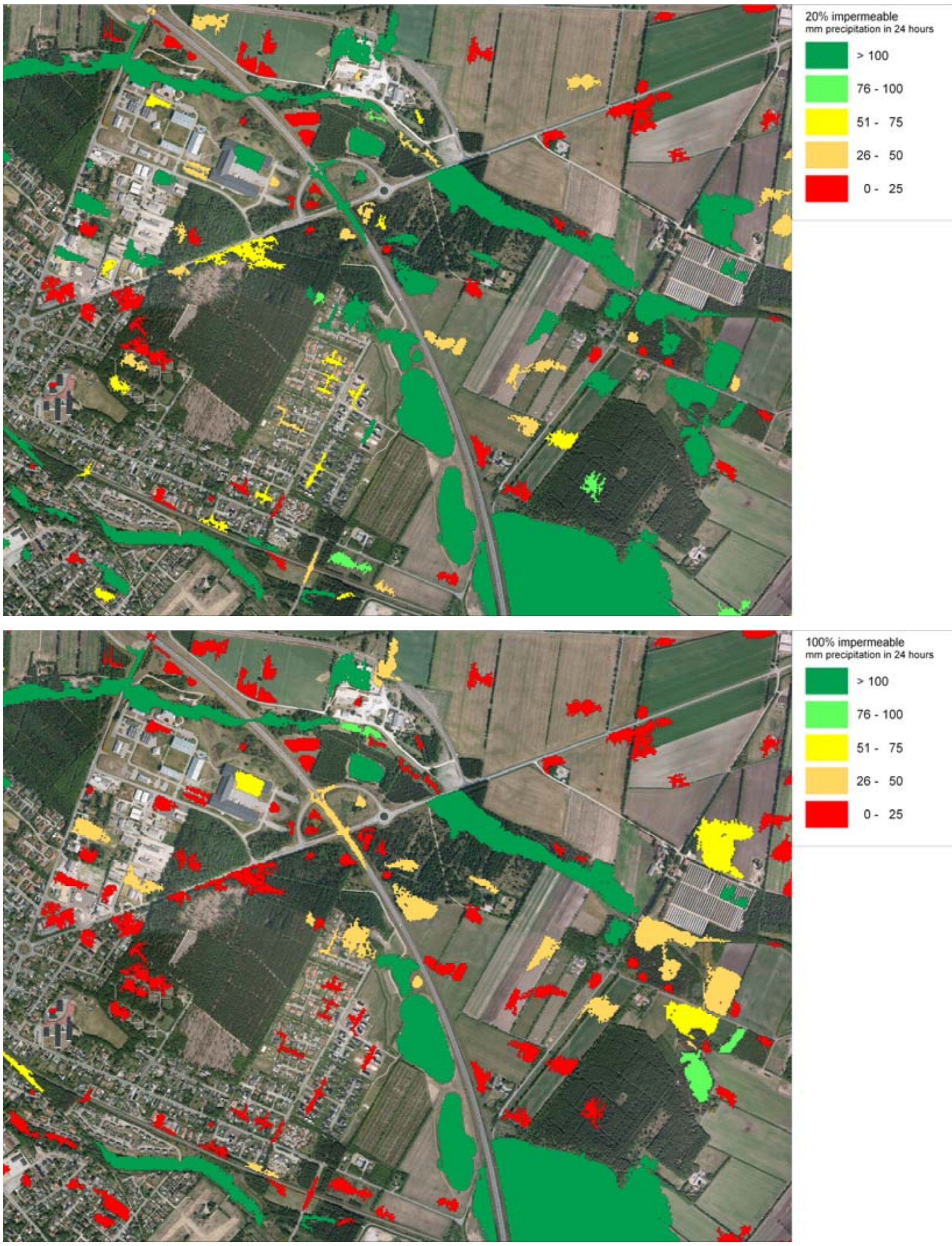

Figure 2. Top: Rain sensitivity analysis with impermeability in the catchment area of 20%. Bottom: 100% impermeability.

LEVEL 3 - Hydrodynamic model of surface reservoirs and depressions

• Provides a time-variable flooding prediction

• 1d-1d Coupling between the surface (terrain, canals and ponds) and drainage systems (pipes), e.g. Boonya-aroonnet (2007), Jensen et. al. (2010).

• 2d-1d Coupling between surface and drainage systems e.g. Nielsen et. al. (2008), DHI (2009), Wallingford (2009), Domingo et. al. (2009). See Figure 3.

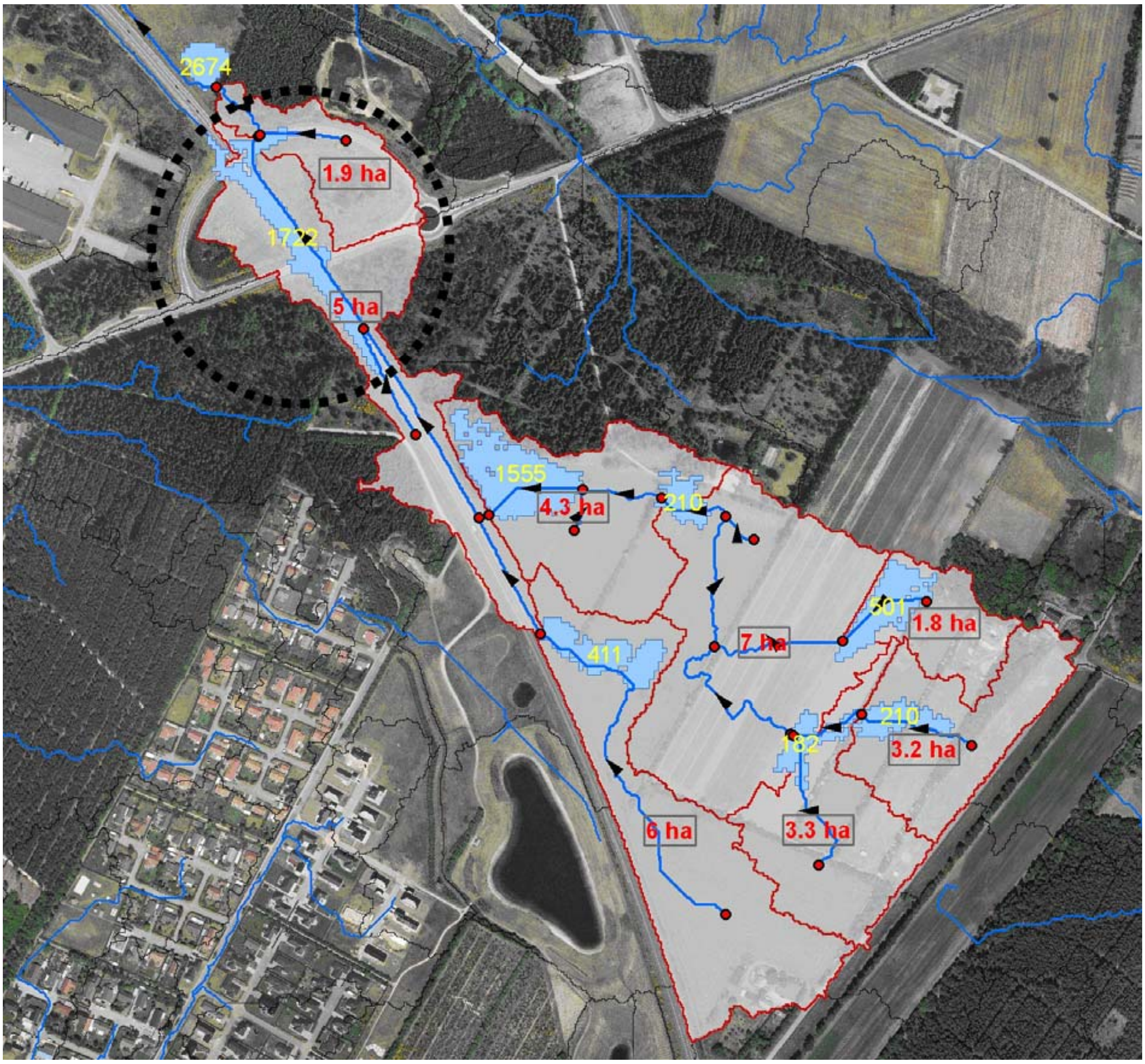

Figure 3. Pathways, catchments and ponds in a risk area are calculated by the use of 1D-1D and 1D-2D modelling.

Focus is on level 1 and 2 and the method is demonstrated for national roads in the area shown in Figure 4. The outcome is used as a tool to prioritise the efforts needed for adaptation.

Furthermore, an example of an analysis of level 3 is included using 1D-1D modelling. Mike Urban (Mike Urban, DHI 2010) was used as the hydrodynamic 1D model. The 1D model simulates the hydraulic pathways and connections between ponds and streams.

Water was routed between the blue spots by pathways identified in the Digital Terrain Model (DTM, see chapter 2.1 page 14). A Manning number of 30m$^{1/3}$/s was used to represent a rough surface runoff (Davis, 1952). Since no information was available on the pipe network this was ignored. Instead a sensitivity analysis was 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 hinterland catchment. Calculations were made using a Chicago Design Storm (CDS) with a return period of 100 and 500 years. A concentration time of 14 min. 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. In Denmark, the factor is recommended between 1.2-1.5 depending on the return period (Arnbjerg-Nielsen et. al. 2008).

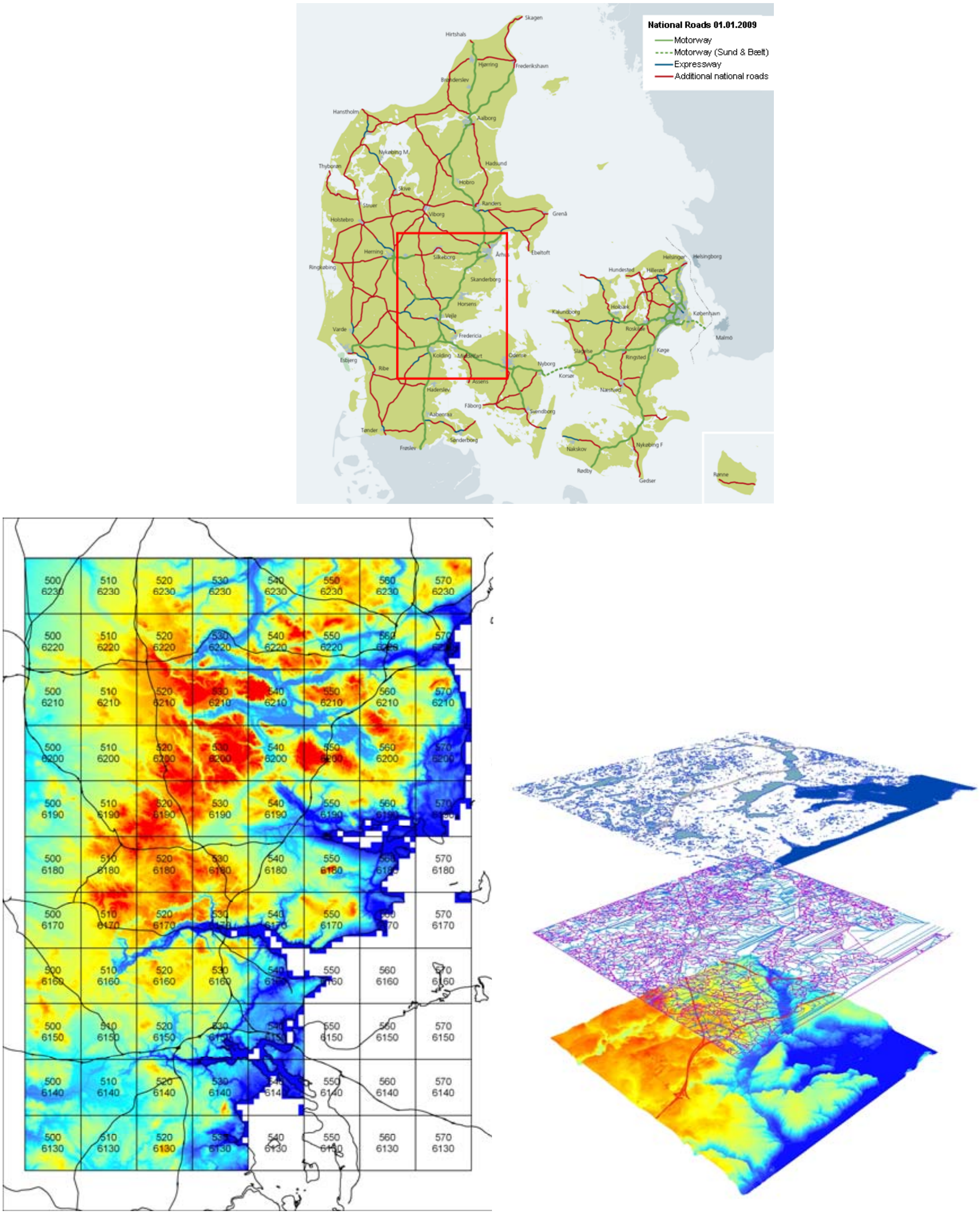

Figure 4. Study area and data. In this area there is a total of 875 km of national roads. Total length of all national roads in Denmark (January 2009) was 3790 km.

The benefits of implementing level 3 are that both the water flow on the surface and in the drainage systems is taken into account thus giving a more accurate calculation of flood risk. Level 3 is an excellent tool to use when looking for a solution, including more details about the systems (e.g. drainage and storage capacity) and when setting up emergency plans.

2.1 Data used in the analysis

The basis for calculating the areas at risk of flooding is laser scanned elevation data for a large part of Mid-Jutland. Laser scanning (see next paragraph) gives a rough terrain model, DSM (Digital Surface Model), including buildings, vegetation etc. The DSM model is then modified such that elements like buildings and trees are removed. The result is a DTM (Digital Terrain Model). Bridges, tunnels, viaducts and waterways will not always appear with underpass in the terrain model. It is therefore necessary to assess whether there is possibility of free passage through these. For this assessment the GIS layers used contain information on locations of bridges on the national roads in Denmark. Furthermore, there are applied maps showing the location of watercourses and aerial photos are used for evaluation of bridges and underpasses.

Elevation data was provided by the Danish Road Directorate in 75 parts of 10x10 km each. Grid data is available at 1.6 x 1.6 m (commonly used in Denmark) and a height accuracy of 10 – 25 cm at well-defined surfaces. Each 10x10 km part thus consists of 39,062,500 points. The whole model contains 2.9 billion points, which set a high requirement 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 m x 1.6 m grid). To perform the analysis in this project, it has been necessary to divide the total terrain model (75x10 kmx10 km = 7500 km^2) into three parts. This is done due to calculation speed and limitations in software used. It gives an uncertainty of results where national roads cross the splitting boundaries.

There are areas in the terrain model that contain missing data ("null value"), for example a line of 1.6 metres in y-direction and 1 km in x-direction. This may affect the results of the terrain analysis. It is chosen not to correct the data (e.g. by interpolation), because it is estimated that there is little overlap with national roads.

It should be noted that the terrain model reflects the date when overflying was done (2006-2007). This means that 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 has been no scanning during periods of major crops, snow and major quantities of melt water. The Coordinate system is UTM zone 32N and the vertical reference system DVR90. Terrain models, including a breakdown of the data used is shown in Figure 5.

There are also cases where a correction of the raw data in area of national roads has been made. Underpasses of piped rivers and streams will appear as obstacles in the terrain model. Figure 6 shows an example of the obstacle effect. All found underpasses are included in the DTM and the water can pass leaving no blue spot (right hand Figure 6).

2.2 Data processing

Risk areas are identified solely on the basis of depressions in the terrain. Ranking in relation to precipitation, 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.

All depressions are filled with water, and by calculating the difference in height compared to the original terrain and the spatial distribution of the depressions it is possible to calculate the total volume of the depression.

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 to create false blue spots. To verify this DTM-GIS layer, information from a database regarding locations of bridges on the national roads in Denmark was used. Furthermore, maps showing the location of streams and rivers and orthophotos were applied. In some locations, the bridges have already been processed. An example is shown in Figure 5 where the raw terrain data have been modified and the elevation data corresponds to the viaduct below the motorway (the bridge has been removed). This result in a depression on the motorway, but in reality the depression is below the motorway.

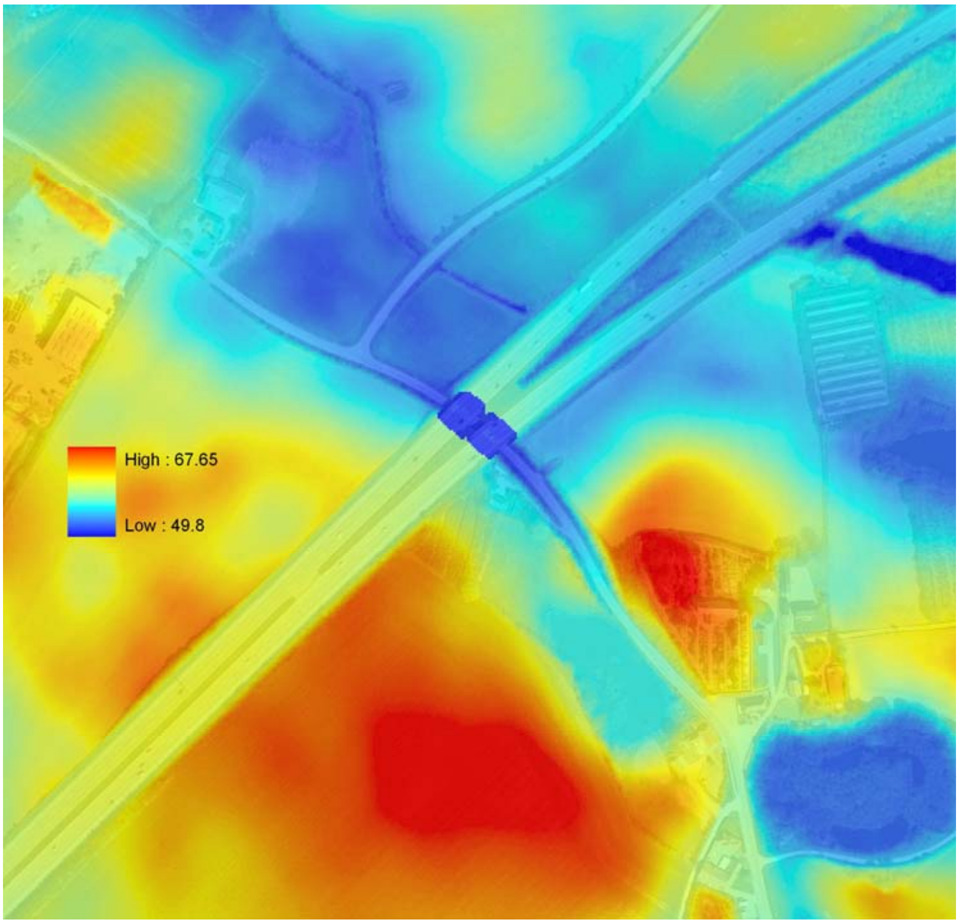

Figure 5. Example of pre-processed bridge data.

There are 221 identified bridges and other crossings of which 98 are reported by the Danish Road Directorate.

These 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. An example of the effect of including these underpasses is shown in Figure 6. In the left hand part of the figure the motorway appears as an obstacle for the river. This is corrected in the right hand part where the obstacle is removed manually in the DTM and the river can pass. By doing this manually operation it is possible that we might introduce an error, because the river can perhaps discharge more water than the piped stream under the bridge can handle, and in this way we remove a potential blue spot.

The effect of sea level rise is assessed by use of the DTM and a water level value representing sea level conditions has been analysed. The terrain model can provide information as to where water from the sea can move onto the coast, accumulate and cause damaging flooding. The depth of flooding over a cell is computed by subtracting the land elevation from the water level.

In the same way it is possible to simulate the flooding effect from rivers. The terrain model can provide information as to where water from the river can move upstream. In the model each given elevation curve can be used as a maximum level of flooding from a river. The depth of flooding over a given cell can then be computed by subtracting the land elevation from the water level, showing a map with the extend of flooding of the river. It is partly shown in Figure 6 (left hand), where the river is flooding upstream due to the downstream blockage.

For the calculations in level 1 and visualisation of results, a method was developed that uses the facilities in the ArcGIS environment (Desktop, Spatial Analyst, 3D Analyst, etc.), i.e. software from ESRI (www.esri.com). 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.

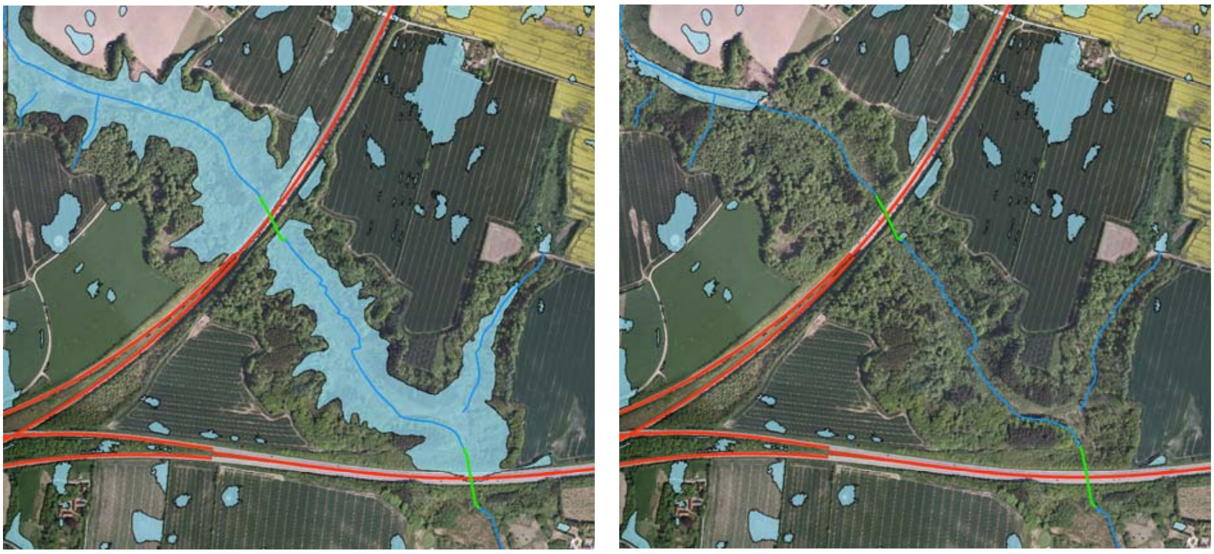

Figure 6. Blue spots before the barrier in the DTM is removed around Sønderjyske Highway and Taulov motorway (left). A distribution of blue spots after an underpass has been introduced in the DTM (right).

3 Results

GIS-themes are digital layers representing information of only one item in each layer (theme) e.g. the GIS-theme with roads contains only geographical information about roads. In the same way with rivers, wetlands, forests etc. The following maps are the results extracted from the various GIS-themes, which are calculated for the whole area. The themes are in sets of polygons, polylines and raster (grid files). The themes are not dependent on a particular GIS system, which is an advantage because of the different platforms used for planning purposes.

3.1 Sea level rise

In case of sea level rise, national roads in the coastal areas may be flooded. Three scenarios for future sea level rise were studied, where the increase was 1, 2 and 3 metres respectively. All elevations lower than a given higher sea level, and in contact with the sea, were considered flooded, which after calculation resulted in polygons that define areas which are flooded (Figure 7). Seven potential risk areas are marked by a circle in the figure. Figure 8 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 in lakes and the groundwater table 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.

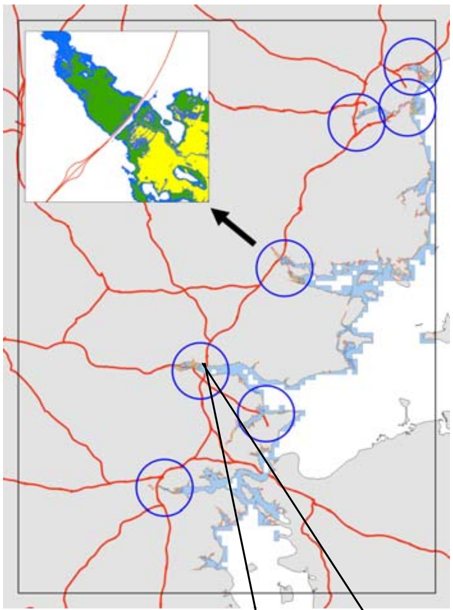

Figure 7. Calculated sea level rise and potential blue spots and zoom showing 1, 2 and 3m rise.

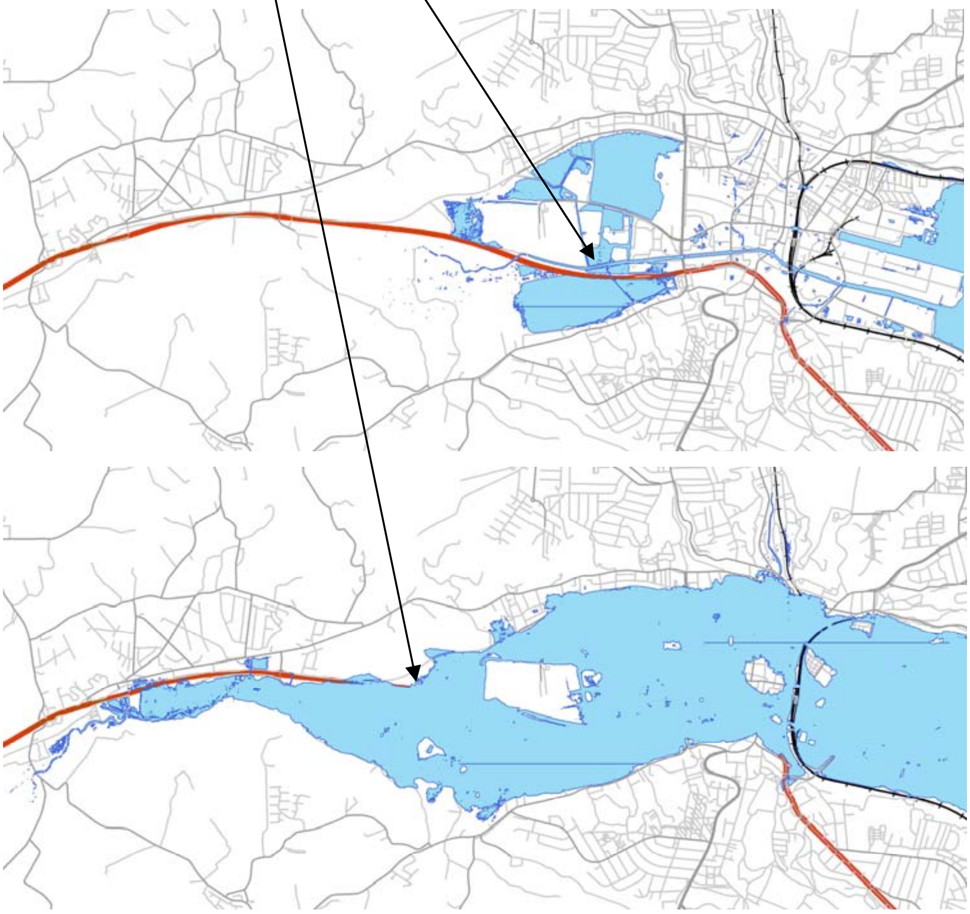

Figure 8. Zoom on to city of Vejle with a sea level rise of 1m (top) and 3m bottom.

3.2 Depressions, preferential flow paths and catchment area boundaries

By making a calculation where all depressions are filled up, and then calculating the height difference compared to the original terrain, spatial distributions and size of depressions are obtained. In addition, the calculated volume of the depression is achieved.

All depressions with a volume greater than 10 m^3 are extracted from the calculation as polygons, since this is considered an appropriate level of detail. Information on area and volume are in the tables attributes belonging to the theme. Calculations are made of highest level of detail (grid 1.6 m x 1.6 m) around national roads (1 km buffer), and a coarser resolution for the entire elevation model (4 x 4 m and 5 x 5 m).

In a calculation of the potential flood areas (blue spots) it is assumed that all surfaces are impermeable, i.e., there is no possibility of leaching or runoff via drains or any other drainage system. The maps show potential risk areas - namely depressions in the terrain where there is a possibility that water can gather and cause flooding. The map material shows the distribution of blue spots with information about size and volume of the depression, and maximum depths of the blue spots.

Figures 9 & 10 shows examples of the calculated maximum depths in some blue spots. In Figure 9 all depths are shown, but it can also be chosen to view the depths of the depressions with a volume greater than e.g. 10 m^3. Calculations are made for the entire terrain model in the highest resolution, corresponding to depths shown in Figure 9.

By using the terrain model, waterways and catchment area boundaries can be calculated, i.e. which way the water flows on the surface from depression to depression, and the geographical distribution of the associated catchments. The size of the catchment lies in the table belonging to the theme. Initially a minimum threshold for the waterways of 1 hectare is selected, i.e. waterways that have an upstream surface area less than 1 hectare are not included. For each depression greater than $100m^3$, a catchment is calculated, if the upstream area is at least 1 hectare.

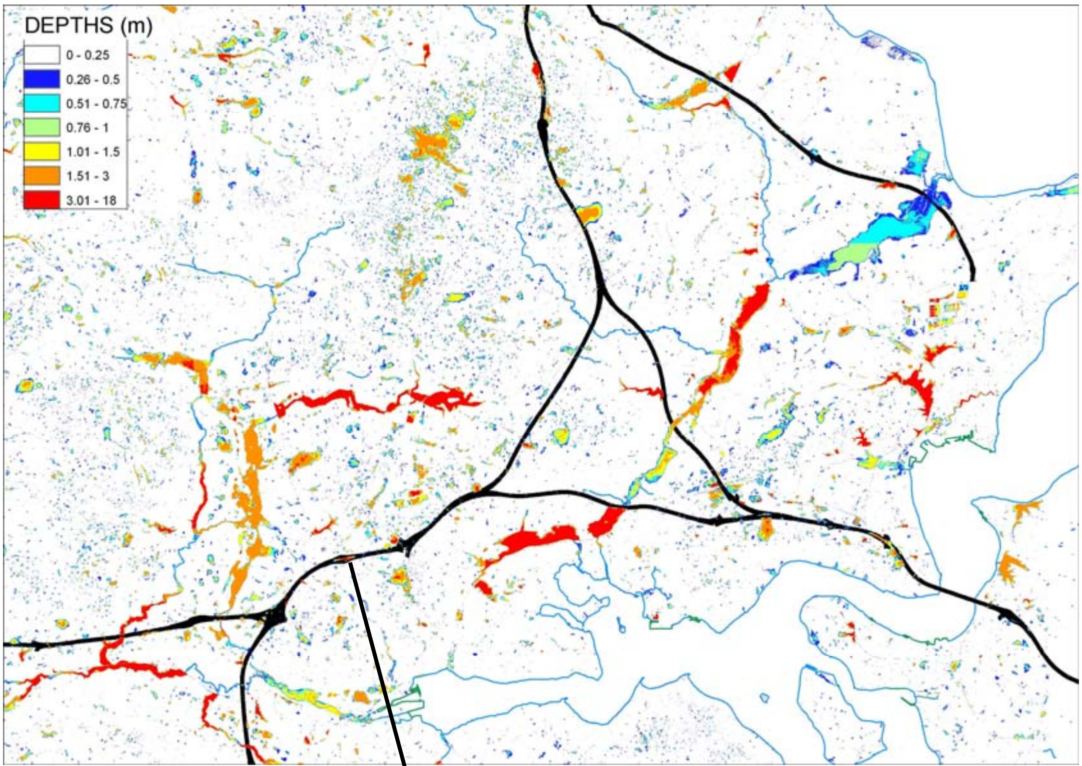

Figure 9. Examples of depressions, which have information about area, volume and depths.

Figure 10. A magnified blue spot with water depths above surface.

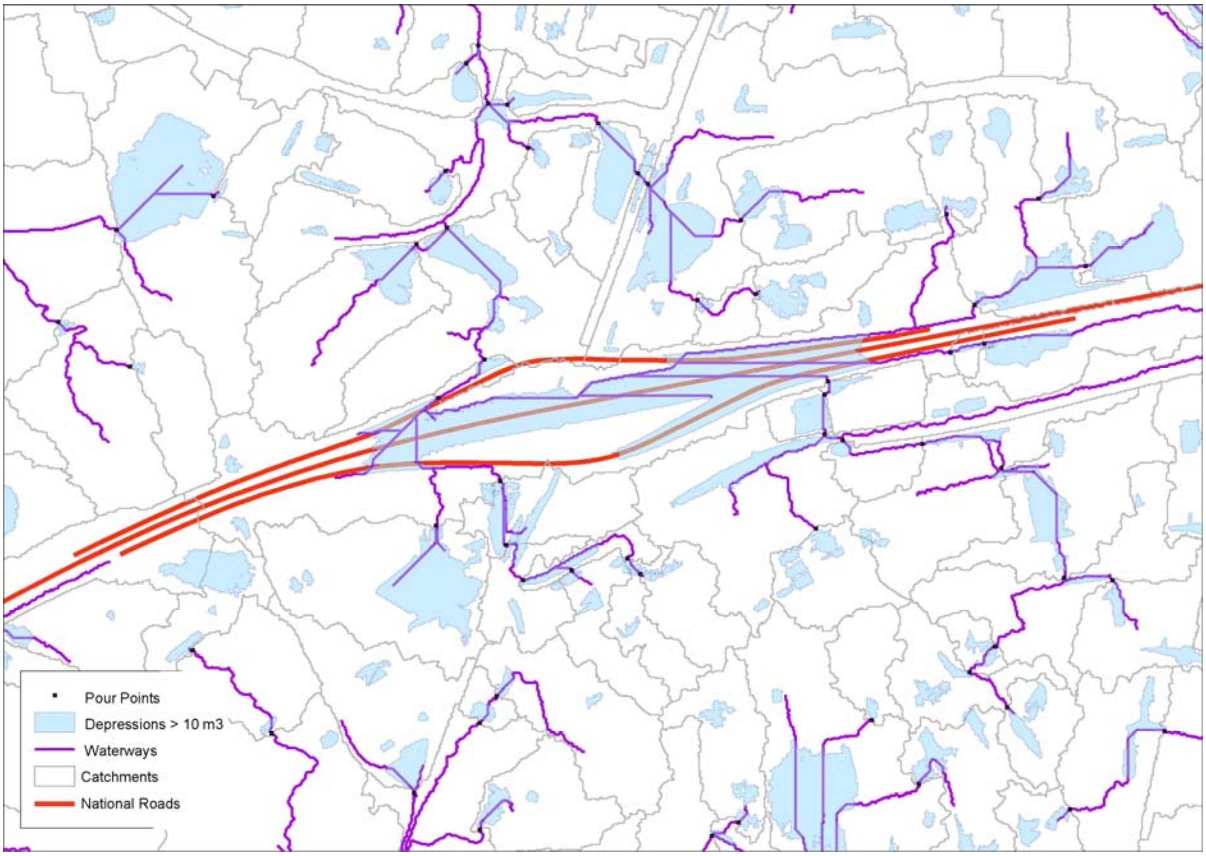

Figure 11. Waterways and catchment areas for a region at the Sønderjyske motorway between Kolding and Fredericia.

In Figure 11, the waterways (purple lines) and the basin boundaries (gray lines) to the same depression are shown. There are also shown points used as input for the calculation of catchment areas, i.e. "pour points" from the depression.

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

A theme calculated can be used to assess the rain sensitivity of the depressions around the national roads. The assessment is at a general level, taking only the adjusted terrain model into account in the analysis (with underpasses). The theme is depressions greater than 100 m^3 with indication of how many millimetres of rain needed to fill the depressions. Catchments and preferential flow paths are at least 1 hectare in the analysis.

The assumptions are that there are estimated runoff equivalents to runoff coefficients of 20 -, 40 -, 50 -, 60 -, 80 - and 100% of the catchment. It is estimated that there is no exchange of water between catchment areas, i.e. each depression and associated catchment is considered separately. Furthermore, no storage in small depressions (<100 m^3) is estimated within the boundaries of the catchment and in depressions greater than 100 m^3 with a catchment less than 1 hectare, if one exists.

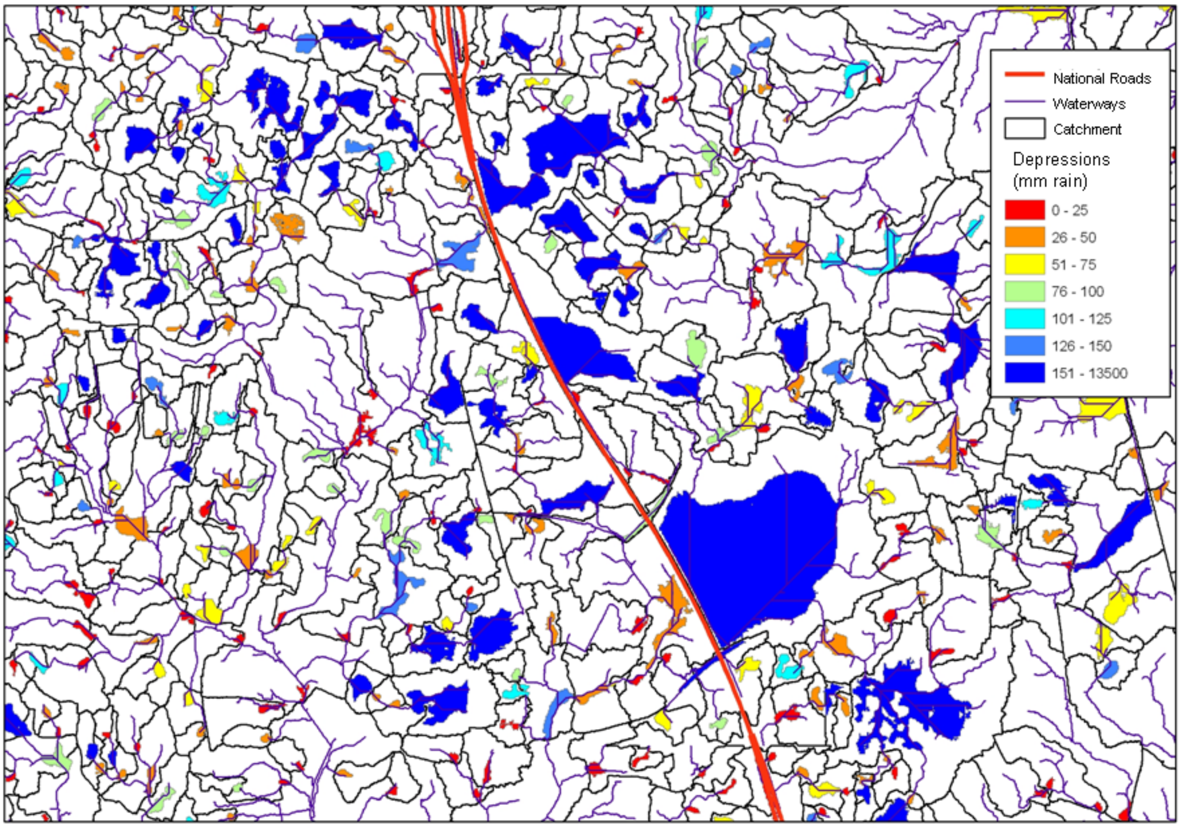

Figure 12. Depressions with flood risk illustrated by the precipitation needed to fill the depression.

Given that depressions and associated catchments are determined, the volume may be related to the size of the catchment. A large catchment area for a small basin provides a greater risk than a small catchment with a large basin. Rainfall depth in millimetres needed to fill the blue spot up can be calculated by dividing the depression volume with the reduced catchment area.

Depressions can be colourised according to the input of precipitation rain, see Figure 12, e.g. depressions can be coloured in red if it should be explored further, because it takes less than 25 millimetres of rain to fill them up.

After a prolonged wet period there is a higher risk of surface runoff from the surrounding catchments. The table 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. In Figure 13 & 14 the precipitation with a runoff coefficient of 20% and 100% respectively are shown.

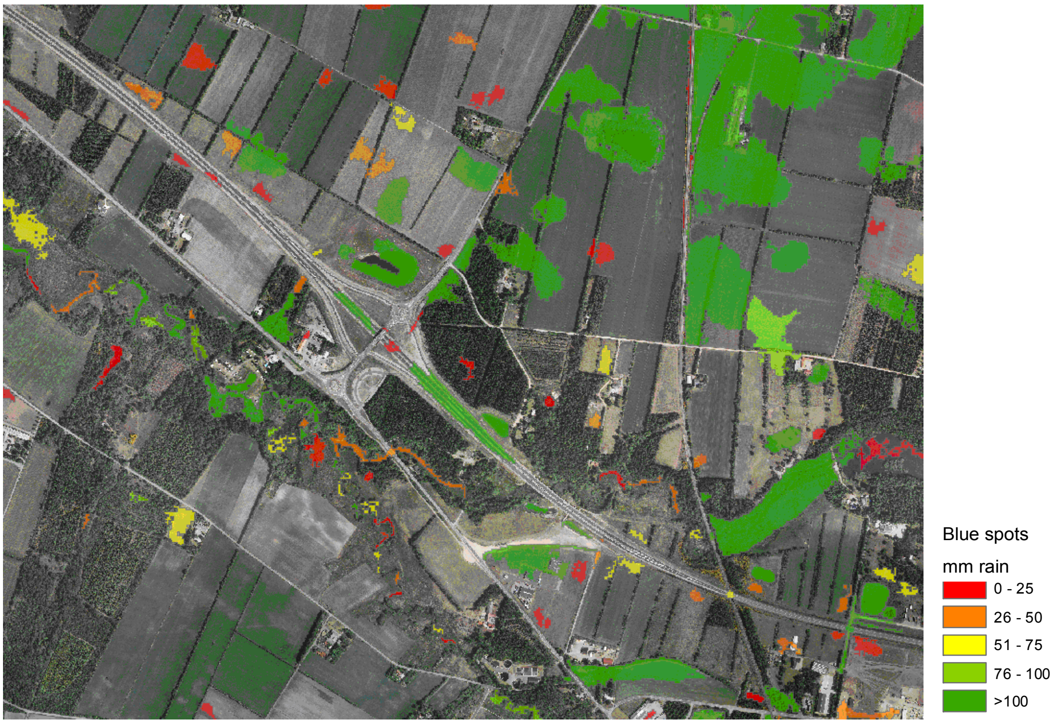

Figure 13. Runoff coefficient 20%.

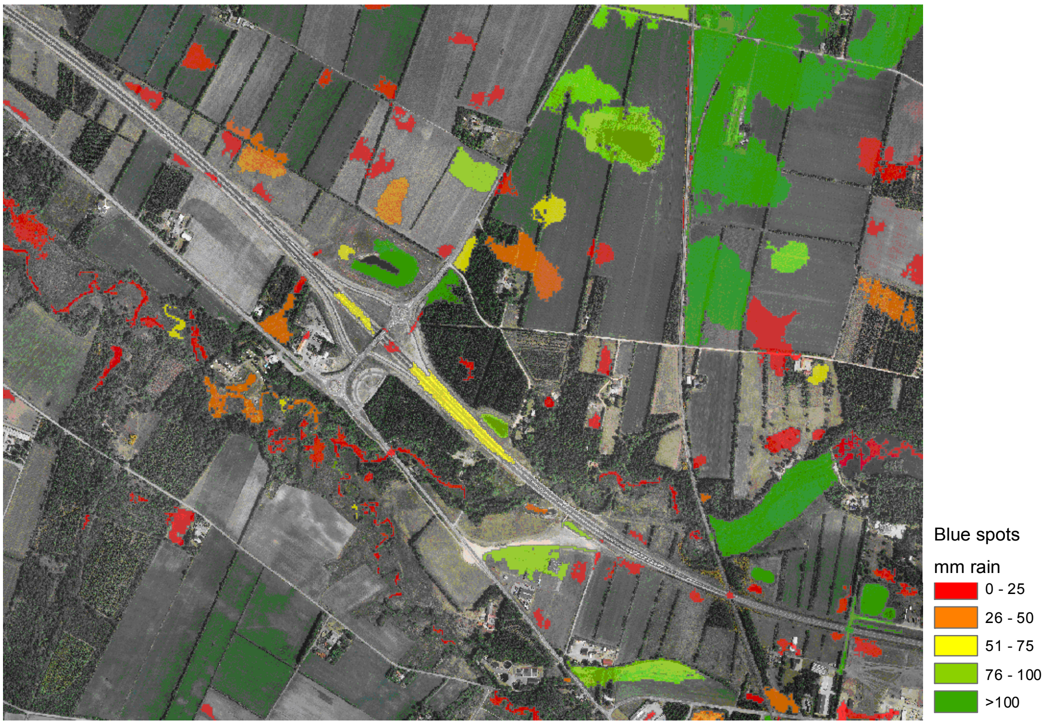

Figure 14. Runoff coefficient 100%.

3.3 Example of a flood analysis at Level 3

In the following, a calculation was made at level 3 for an area at risk of flooding. The area is located near Brande, in Jutland, where a road crosses a local depression of approximately 1700 m^3 with a maximum water level of 0.5 m on top of the road. A detention basin (~2600 m^3) is placed downstream the depression. The contributing area upstream of the depression in the vicinity of the road was identified (Figure 15). The runoff coefficient, roughness coefficient etc. are estimated data. The data derived from levels 1 and 2 according to Table 2 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.

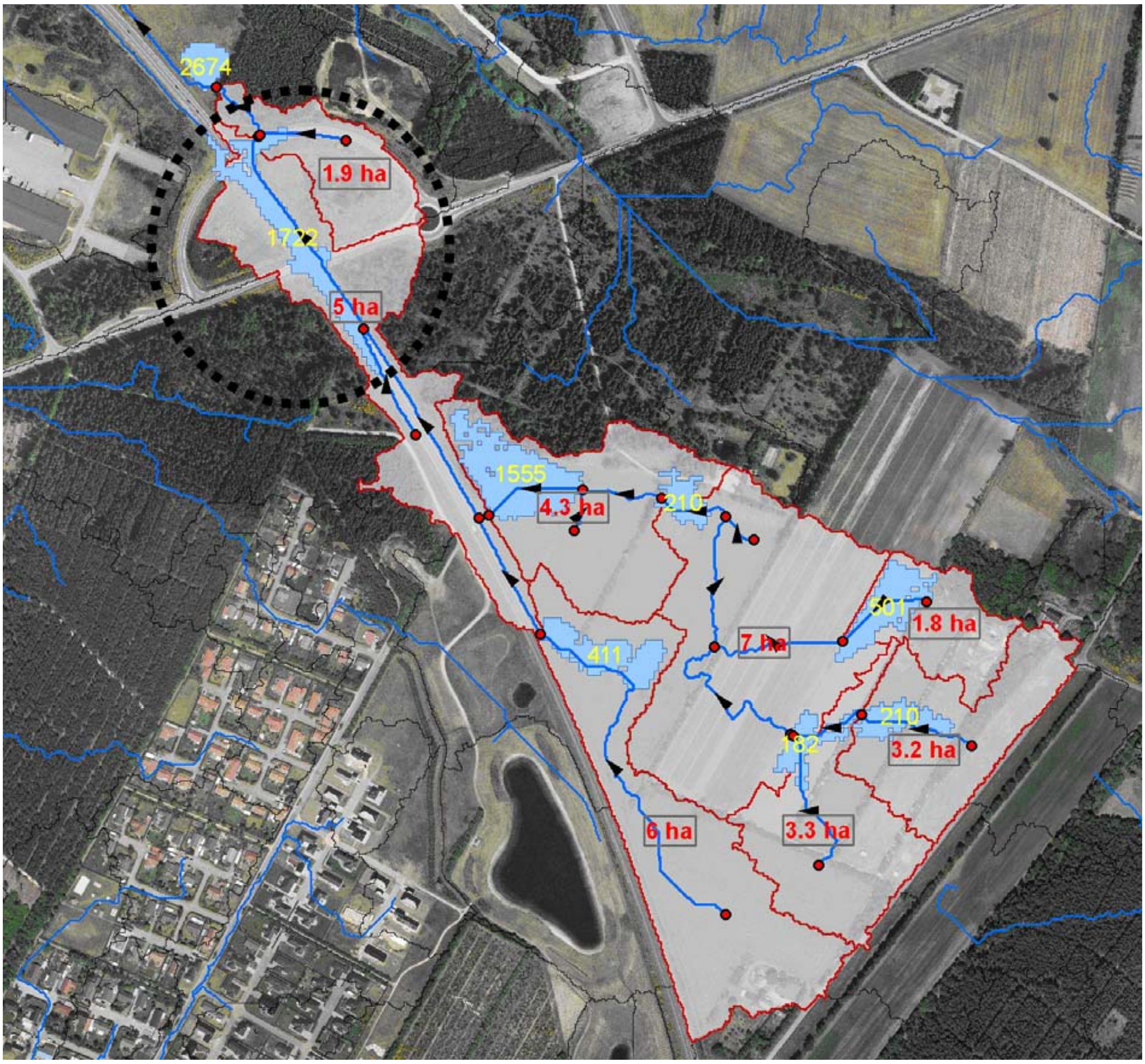

Figure 15. Risk area identified.

Below are listed the results of the rain events with and without climate factor (Table 3). 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 analyses of the drainage capacity of the road by calculating different retention times depending on the drainage capacity.

Figure 16 shows the calculated maximum water depths. The flooded area under the bridge deck has a larger extent than the width of the road. This is due to the removal of the bridge deck in the original terrain model, see previous chapter 2.2 and Figure 16 (low, right) where the bridge is replaced by a low lying section. Thus, the water levels (z-levels) under the bridge are not all valid, and the calculated depression volume and water depths were thus affected. That there is less depression volume available in reality will lead to a wider dissemination of the flooding than seen in these figures.

For return periods of 500 years, the low lying area under the bridge will be completely filled and water will start to run downstream (Figure 16, low right).

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.

Table 3. Results for events with and without a climate factor.)* Depression is filled!

Scenario	Max. depth (cm)	$Q_{max,inflow}$ (l/s)	Accum. vol. (m^3)	From upstream depp. (m^3)	Max Vol. (m^3)	Time until empty (5 l/s)
T100 year (CF=1)	32	229	817	0	425	24 hours
T500 year (CF=1)	39	323	1232	175	720	40 hours
T100 year (CF=1.4)	40	323	1310	211	771	43 hours
T500 year (CF=1.4)	59 *)	436	2900	1482	2010	112 hours

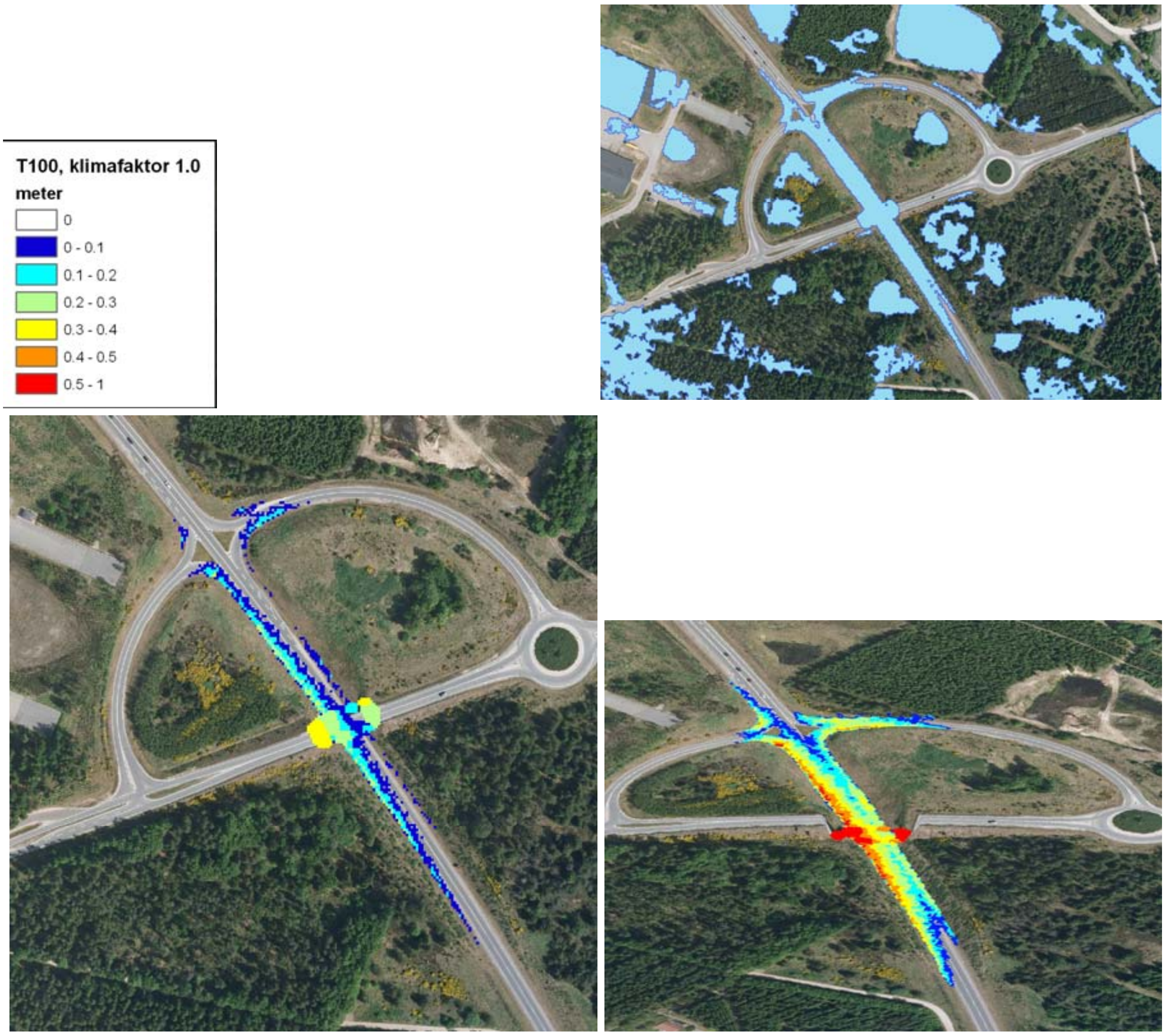

Figure 16 Showing depressions using level 1 (top) and calculated maximum water depths for T = 100 years (CF=1.0) (low left) and T=500 years (CF=1.4) (low right).

3.4 Flood risk maps

The results of the calculations at level 1 are maps showing critical sections as points (Figure 17 & 18).

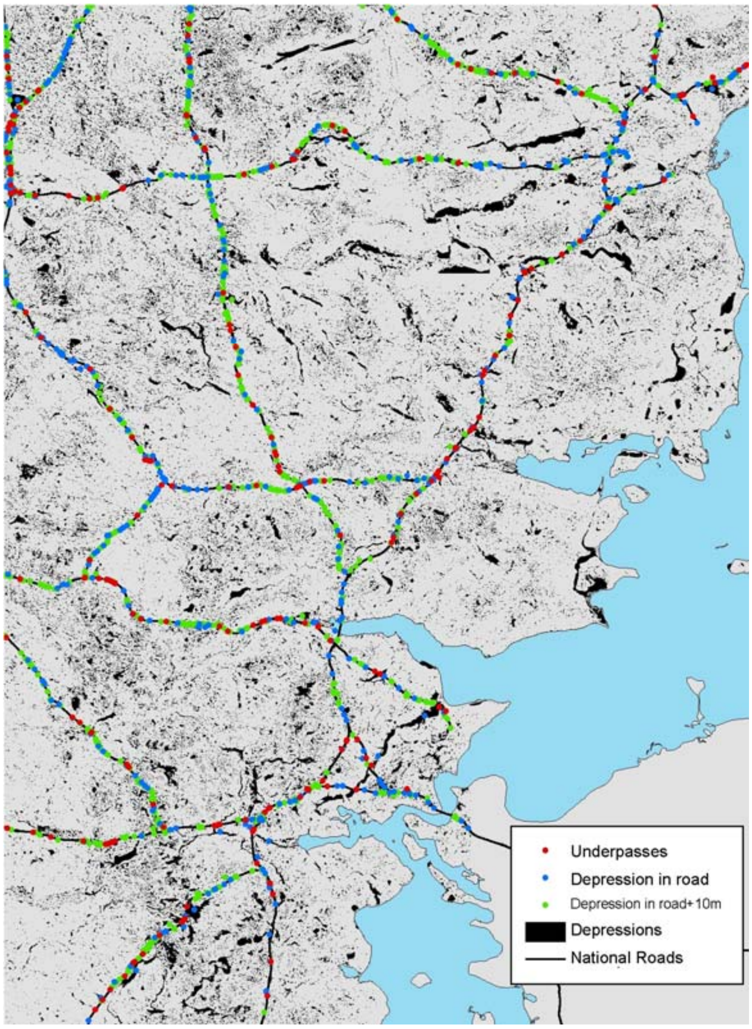

Figure 17. Critical areas for the whole computed area.

These points mark 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.

Flood maps could be used as part of a ranking of depression in relation to 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 depression in relation to the road area, and how many millimetres rain are needed to fill the depression.

The data from the flood maps allows for the establishment of a contingency plan for extreme situations. Flood maps can provide valuable information about the measures that should be taken to reduce damage if and when extreme events occur.

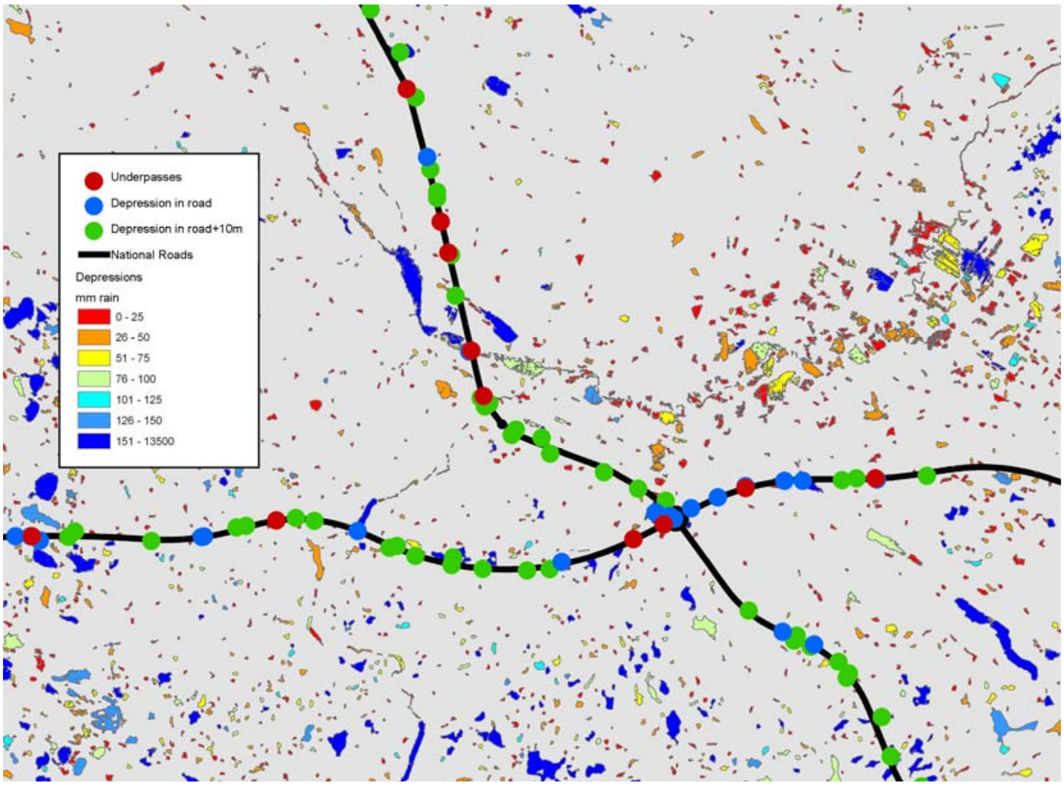

Figure 18. Magnified areas from Figure 17. An example of how to prioritise in relation to the amount of precipitation needed to fill the depression.

3.5 Risk analysis

After pointing out all the 'blue spots' on the road network on a level 2 basis, it is often necessary to minimise the numbers for further evaluation. It can be done by a risk analysis as illustrated in Table 4. The table shows the matrix of a simple risk analysis where the left column gives the probability of an event e.g. some of the rain fall events will probably never happen, for example between 151-13500 mm/day as shown in Figure 18. This type of event can be categorised as 'Unlikely' or 'Rare', using Table 4.

Table 4. Risk analyse matrix. The probability is in left column and the consequences are on the top row.

	Insignificant	Minor	Medium	Major	Catastrophic
Certain					
Likely					
Possible					
Rare					
Unlikely					

The consequences for the road users and the roads are illustrated at the top row in Table 4. The same rain fall event can have different consequences for different types of roads. The numbers of users also have an influence on the consequences, e.g. stopping 500 road users due to a 'blue spot' does not have the same consequence as stopping 5000.

After each blue spot has been categorised with a 'probability' and a 'consequence' it can be plotted in the matrix in Table 4.

All blue spots plotted in the red are road network areas in the 'high risk end' of the scale and should be the blue spot areas for a further evaluation using the level 3 step described in this document.

Some of the blue spots plotted in the orange area of the matrix are questionable for a further examination, but even 'Unlikely' events can be 'Catastrophic'.

Along with further examination using level 3 of the GIS-analysis all the blue spots can be evaluated by office personnel and field personnel using the SWAMP Report 4: *Inspection and maintenance. Guide for reducing vulnerability due to flooding of roads.*

4 Conclusion

A method for screening large areas for flood risk on national roads in Denmark is described in this part of the project 'SWAMP'. The analysis is divided into three levels where each level provides better knowledge 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 the rain sensitivity of the blue spots, while level 3 includes detailed hydrodynamic modelling of the surface flow. As knowledge increases gradually with the different levels, the numbers of areas at risk are reduced. The methods were tested and applied on a large area in the middle and southern part of Jutland in Denmark. The outcome of the analysis was valuable flood risk maps that will help prioritise the efforts as the road sector adapts to climate change.

Focus has been on level 1 and level 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 is 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. For both long term investment and ad hoc solutions a tool is now available that will ensure that the same priority model can be used.

5 Recommendations

The SWAMP project group recommends to the national road administrations to use the GIS model for blue spot identification. The Blue Spot Model can be used as a tool to identify vulnerable paths of the road network system. The Blue Spot Model is not only a tool to identify the vulnerable paths due to the existing climate, but can also be used to predict points of blue spots in a future climate. In this way the National Road Administrations can use the Blue Spot Model to prioritise the maintenance, inspection and repair of each blue spot, using the outcome of another ERA-NET ROAD project: RIMAROCC: Risk Management for Roads in a Changing Climate, which is a specially designed risk management system developed explicitly for road owners.

Furthermore the Blue Spot Model can be used as a tool in the planning phase for new roads by finding all the depression in the landscape and thereby it is a helpful tool to design the new road sections by bypassing the most obvious blue spot areas.

Table 5 lists the maps, software and the technical input which have been used in this project. This list is referred as 'Nice to have' and gives the most detailed Blue Spot Model. The right part of the table lists the items 'Need to have' to make a Blue Spot Model.

Table 5. List of 'Nice to have' and 'Need to have' to make the Blue Spot Model

Nice to have	Need to have
Laser scanning (LiDAR) : Grid size 1.6 m x 1.6 m, giving one point with x,y,z coordinates for every 2,56 m^2 and a resolution for each z-point (elevation) of 0,1 – 0,25 m	Maps in digital form with elevation curves. Contour distance can be from 1m to 20m or higher, but greater elevation distance between the curves will lower the resolution of the model.
Arial photos for verification of bridges, tunnels etc.	If no arial photos exist GOOGLE Earth is a possible alternative. It is for free on the internet and is rather fast to work with
Technical maps (roads, houses, rivers, etc) in digital form.	Technical maps (roads, wetland areas), in digital form. These maps are at least needed to verify the outcome of the model.
Database with information on bridges, river crossings etc.	GOOGLE Earth is a free alternative to create a database with information on bridges, river crossings etc.
ArcGIS Desktop program for the GIS calculations	MAPINFO for GIS calculations Or some of the free open source programs downloaded form the internet. e.g.: QGIS: www.qgis.org MAPWindow: www.mapwindow.org GRASS GIS: www.grass.itc.it

1D-1D & 1D-2D modelling: MOUSE & MIKE URBAN software: www.dhigroup.com	If the model is lifted to the level 3 analysis following software components can be used as an alternative to the DHI-software. There are no free/open source 1D-1D & 1D-2D modelling components on the internet (at least we have not found them!) DELTARES software: www.wldelft.nl WALLINGFORD software: www.wallingfordsoftware.com TUFLOW software: www.tuflow.com

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Appendix 1 Abbreviations and definitions

Phrase	Description
A2	A2 is one of the six families of scenarios discussed in the IPCC Third Assessment Report (TAR) and Fourth Assessment Report (AR4). The families are A1FI, A1B, A1T, A2, B1, and B2. The A2 scenario family represents a differentiated world. Compared to the A1 storyline it is characterised by lower trade flows, relatively slow capital stock turnover, and slower technological change – among many others things.
AOGCM	Atmosphere-Ocean Global Climate Model
AR4	Assessment Report 4 by IPCC in 2007
ArcGIS	ArcGIS is an integrated collection of GIS software products that provides a standards-based platform for spatial analysis, data management, and mapping. ArcGIS is scalable and can be integrated with other enterprise systems such as work order management, business intelligence, and executive dashboards.
B2	B2 is one of the six families of scenarios discussed in the IPCC Third Assessment Report (TAR) and Fourth Assessment Report (AR4). The families are A1FI, A1B, A1T, A2, B1, and B2. The B2 scenario is one of increased concern for environmental and social sustainability compared to the A2 storyline.
Blue spot	A blue spot is a part of a road that is vulnerable to flooding, either by precipitation, catchment water or sea level rise. The term blue spot is self-made, inspired by “black spots” referring to places with many traffic accidents. The blue spot needs enough water to cause a dangerous situation for road users, more than a normal aquaplaning risk. The presence of a blue spot on the road can have a variety of reasons, e.g. road design, damage or underestimation of the drainage system, a saturated catchment, heavy rain etc. A blue spot can be identified by experienced personnel in the field or by GIS modelling. A 1D-2D model for blue spot identification has been developed, using different layers of information, e.g. a digital terrain map, geography, road maps, drainage systems etc. The model can, in a GIS map, show places on the road network, where a blue spot is likely to occur, e.g. under different precipitation intensities. There is likely to be a higher risk of blue spots in the future, if predictions for an increasing precipitation pattern come true.

CDS Chicago Design Storm	A storm whose magnitude, rate, and intensity do not exceed the design load for a storm drainage system or flood protection project.
Depression	A depression is a landform where an area is sunken or depressed below the surrounding area. Depressions will often be the first places that stow water.
DSM Digital Surface Model	Digital surface models (DSMs) are topographic maps of the earth's surface that provide a geometrically correct reference frame over which other data layers can be draped. In addition to the Digital Terrain Model (DTM), the DSM data includes buildings, vegetation and roads.
DTM Digital Terrain Model	Digital surface models (DSMs) are topographic maps of the earth's surface that provide a geometrically correct reference frame over which other data layers can be draped.
EMIC	Earth System Models of Intermediate Complexity
Emission scenario	Scenarios for emission of greenhouse gases. Examples include A1, A1B, A2 etc.
Ensemble	A group of parallel model simulations used for climate projections. Variation of the results across the ensemble members gives an estimate of uncertainty. Ensembles made with the same model, but different initial conditions only characterise the uncertainty associated with internal climate variability, whereas multi-model ensembles including simulations by several models also include the impact of model differences. Perturbed parameter ensembles, in which model parameters are varied in a systematic manner, aim to produce a more objective estimate of modelling uncertainty than is possible with traditional multi-model ensembles.
EU2C	The EU2C scenario, calculated by the Danish Meteorological Institute, is based on the EU objectives that the human induced global warming will not exceed 2 degree Celsius. The scenario is based on A2 and B2.
FAR	First Assessment Report: The first assessment made by IPCC in 1990
GCM	Global Climate Model or Global Circulation Model
GHG	Greenhouse Gas
GIS Geographic Information System	A geographic information system (GIS) allows you to view, understand, question, interpret, and visualise data in many ways that reveal relationships, patterns, and trends in the form of maps, globes, reports, and charts. GIS describes any information system that integrates, stores, edits, analyses, shares, and displays geographic information.

	In a more generic sense, GIS applications are tools that allow users to create interactive queries (user-created searches), analyse spatial information, edit data, maps, and present the results of all these operations.
Greenhouse gas	Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth's surface, the atmosphere itself, and by clouds. This property causes the greenhouse effect. Water vapour (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere. Moreover, there are a number of entirely human made greenhouse gases in the atmosphere, such as the halocarbons and other chlorine and bromine containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the greenhouse gases sulphur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).
Grid cell	The geometric unit (often an area or a volume) in a numeric computer model.
IPCC	Intergovernmental Panel on Climate Change So far responsible for development of scenarios.
Lowland areas	A lowland area is characterised as any broad expanse of land with a general low level. The term is normally applied to the landward portion of the upward slope from sea level to continental highlands, to a region of depression in the interior of a mountainous region, or to any region in contrast to a highland. In these study examples of lowlands are Netherlands, Denmark, southern parts of Sweden, northern part of Germany and Poland and most of UK.
Manning number	Is a constant number for surface roughness and is used in a formula calculating the velocity of the water flow on different surfaces. The number varies between 130 – 20, where the high number refers to very smooth surface and thereby a high flow velocity, and the low number to a very rough surface.
Mike Urban	MIKE URBAN is an urban water modelling software made by Danish Hydrological Institute, and it is a complete integration of GIS and water modelling. MIKE URBAN covers all water in the city, including: • sewers - combined or separate systems or any combination of these • storm water drainage systems, including 2D overland flow • water distribution systems

MMD	Multi-model data set, same as PCMDI
PCMDI	Program for Climate Model Diagnosis and Intercomparison
RCM	Regional Climate Model
RCP	Representative concentration pathways
SAR	Second Assessment Report made by IPCC in 1996
SRES	Special Report on Emission Scenarios
TAR	Third Assessment Report made by IPCC in 2001
1D-1D modelling	1D-1D refers to 1D flow in pipes and to 1D flow in surface pathways and ponds. The hydrodynamic model is a model combining the surface and ponds runoff with the sub-surface runoff. This is done for grid nodes in the terrain and is calculated as water level for each node.
1D-2D modelling	1D-2D refers to 1D flow in pipes integrated with 2D surface flow simulation by taking the water level for each grid node in the 1D-1D modelling and visualising it in a GIS layer, showing the extent and the depth of the depression which gives the 2D in the surface modelling.